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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

NONCOHERENT DETECTION OF COHERENT OPTICAL HETERODYNE SIGNALS CORRUPTED BY LASER PHASE NOISE

by

Kent C. M. Varnum

March 1991

Thesis Advisor: R. Clark Robertson
Thesis Co-Advisor: Tri T. Ha

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As a demonstration of future system capability, the performance of a multiuser FSK code-division multiple access (FSK-CDMA) system is analyzed. The results obtained indicate that the application of FSK-CDMA techniques to current wavelength division multiplexed (WDM) systems can increase user capacity up to one thousand fold.

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Noncoherent Detection of Coherent Optical Heterodyne Signals Corrupted by Laser Phase Noise

by

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Lieutenant, USN
B.S, U. S. Naval Academy, 1982

Submitted in partial fulfillment of the
requirements for the degree of

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I. INTRODUCTION

In 1880, after his work on the telephone, Alexander Graham Bell proposed a device which he called a 'photophone'. Bell's photophone was a device in which the user spoke into a long tube with a metallic diaphragm at the end. Sunlight, reflected on the vibrating diaphragm varied in intensity as the user spoke. A selenium detector then translated these variations into replicated speech at the receiving end through the photoelectric effect. Bell's photophone was the first practical use of light as a transmission medium. Although Bell was able to demonstrate his Photophone over distances of up to 200 meters, it was not accepted by a disbelieving public and forced onto the back shelf of obscurity. It was not until 1966 that the use of an optical dielectric waveguide for high performance communications was suggested by Kao and Hockham [Ref. 1]. At the time, available hardware was insufficient to implement this proposal. Today, optical fiber communications is a highly developed transmission medium which is rapidly replacing standard wire pair and coaxial cable installations. Optical fiber cable has many advantages over other transmission media. Some advantages were projected when the technique was originally conceived, others became apparent only as the technology advanced. Some of these inherent advantages will now be discussed.

Probably the most profound characteristic of optical fiber communications is its enormous potential bandwidth. Because of the extremely high frequencies of the optical carriers used in the system, 10^{13} Hz to 10^{16} Hz, a useable transmission bandwidth of as much as 50 THz may be obtained as compared to a useable transmission bandwidth of only 500 MHz available on coaxial cable. It must be emphasized at this point that the 50 THz bandwidth is a theoretical limit only and has not yet been obtained in practice due to a myriad of current technological shortfalls. The majority of current research is directed toward full bandwidth realization. Current technology provides useable optical fiber transmission bandwidth of several GHz, still vastly superior to current coaxial and twisted pair systems.

Another advantage of optical fibers over their metallic counterparts is their extremely small size and weight. Optical fibers have very small diameters and the unique advantage that the smaller diameter of the fiber, the better its transmission performance. Thus, most optical fibers have a diameter smaller than a human hair, and even when covered with a protective coating, remain much smaller and lighter than coaxial cables and twisted pairs.

Cost is another advantage of optical fiber over metallic cable. At this time, coaxial land cables cost as much as \$4.90 per channel per kilometer, while optical fiber cable meeting the same specifications costs about \$0.56 per channel per kilometer. In addition, the optical fiber requires fewer repeaters, a requirement for long haul communications, further reducing system cost.

Other advantages of optical fiber communication systems include:

- Immunity to interference and crosstalk
- Signal security and jamming protection
- Low transmission loss
- Ruggedness and flexibility
- Easy covert deployment
- Fail safe, no spark hazard
- System reliability and ease of maintenance

The preceding discussion of the virtues of optical fiber communications is not meant to convey the idea that optical fiber is either the perfect transmission medium or fully realizing its potential in todays applications. Currently available components impose serious limitations on system performance and no user to date has established the need for a dedicated 50 THz channel.

Because of the relatively small user bandwidth requirements, todays optical fiber communications systems are extremely useful in multiuser applications. Current lightwave communication systems employ wavelength division multiplexing (WDM) to obtain multiuser capabilities over the vast available fiber bandwidth. In WDM systems, each users transmit laser is tuned to a unique frequency. The users data modulates the transmit laser and all user data streams are optically mixed and transmitted down the optical fiber channel. At the receiver, the composite signal is filtered through a device, usually a prism, to split the optical signal into its component frequencies. The users then detect their individual data streams through a direct detection by a photodetector [Ref. 2]. WDM is the optical analog of frequency division multiplexing (FDM) in radio frequency (RF) systems. The optical systems are degraded by standard receiver noise, shot noise in the photodetector and phase noise in the transmitting laser. The impact of receiver and photodetector shot noise in WDM systems is significantly reduced by the application of optical heterodyne techniques which are very similar to standard RF heterodyne techniques. Unlike direct detection systems, optical heterodyne systems mix a locally generated lightwave with the received signal which is then detected by a photodetector. The resulting electric signal is a replica of the optical signal translated down in frequency, usually to the microwave frequency range. Mixing the incoming optical signal with a local laser provides strong optical input power to the photodetector. The strong local laser condition drastically reduces the effect of the receiver thermal noise and photodetector shot noise. Unfortunately, the addition of a local laser at the receiver increases the effect of the laser phase noise on system performance. Laser phase noise is a noise mechanism inherent to the physical nature of all lasers that impresses random phase and amplitude modulation on the otherwise monochromatic laser output. In optical heterodyne systems, the laser phase noise of the transmit and receive lasers is additive. Current research indicates that in order to attain reasonable bit error performance, the system filter bandwidth must be at least 10 times the sum of the laser phase noise bandwidth of both the transmitting and local lasers [Ref. 3]. Current semi-conductor lasers may have a laser phase noise bandwidth of up to 50 MHz and require a channel bandwidth of up to 100 MHz. For user bit rates much less than or equal to the laser phase noise bandwidth, the channel spacing required in WDM systems to ensure sufficient guardbands results in an extremely inefficient use of available bandwidth.

Future systems will have to accommodate more users with higher bit rates. This thesis addresses the high bit rate systems that will be required by future users. As an extension of current system performance, a single user coherent optical heterodyne binary on-off keying (OOK) communications system with noncoherent detection is analyzed. The analysis shows that as the user bit rate increases relative to the laser linewidth, the impact of the laser phase noise on system performance decreases.

The mathematical analysis of OOK system performance is computationally intensive. The analysis is further complicated by the existing expressions modelling the random behavior of the laser phase noise. Current expressions model the random nature of the laser phase noise in low frequency systems and are either extremely complex or empirically derived approximations. This thesis derives a compact closed form expression for the random variable determined by the laser phase noise. The expression is derived based on a high bit rate assumption and improves upon empirically derived expressions in that it mathematically models actual laser phase noise. The system performance obtained with this expression is compared with the system performance obtained with currently used expressions to determine the range of its validity.

The effect of the normalized decision threshold setting on OOK system performance is also studied. Previous work on OOK systems corrupted only by additive white Gaussian noise indicates that the ideal normalized decision threshold is 0.5 [Ref. 4]. Recent works analyzing the performance of low bit rate OOK systems corrupted by additive Gaussian noise and laser phase noise indicate an ideal threshold setting of 0.3 [Ref. 5]. The ideal threshold for high bit rate systems is found to be also in the vicinity of 0.3, and an analysis of the threshold setting for a non-adaptive threshold system is conducted.

This thesis next investigates the performance of an optical heterodyne binary Frequency Shift Keying (FSK) system with noncoherent detection. The probability of bit error performance of the noncoherent FSK system exceeds that of the noncoherent OOK system. The improvement in the performance of the FSK receiver is due to the fact that the symmetry of the receiver dictates an ideal decision threshold of zero. The zero threshold is valid for FSK systems corrupted by both additive Gaussian noise and laser phase noise.

As a means of improving the multiuser capacity of high bit rate optical communications systems, this work proposes the implementation of code-division multiple access (CDMA) techniques in the FSK system. CDMA is a type of spread-spectrum that adds multiuser capability by spreading and despreading each user data signal with a unique digital code. Each system user is assigned a particular code sequence which is used to encode each data bit. This thesis considers the use of two types of spreading codes, random codes and Gold codes. Random codes are constructed of a sequence of random variables taking values $\{+1, -1\}$ with equal probability, and the sequences assigned to different users are mutually independent [Ref. 6].

Modelling spreading codes as random is desirable for analytical purposes but impractical to implement [Ref. 7]. Actual systems use pseudorandom code sequences to approximate true random code behavior. A commonly analyzed set of pseudorandom codes are Gold codes. Gold codes are constructed from maximal length sequences (M-sequences). M-sequences consist of N elements taking values $\{+1, -1\}$. The elements are arranged so as to give the sequence as random an appearance as possible. A set of Gold codes is constructed from two M-sequences. The set contains the two original M-sequences as well as $N-1$ additional sequences constructed from the modulo two addition of the two M-sequences shifted one element at a time relative to each other [Ref. 8]. The resulting set of Gold codes exhibit near random behavior. The numerical analysis of the FSK-CDMA system is conducted for both random and Gold codes so that actual performance of Gold codes may be compared with the ideal performance of random codes. In order to distinguish between user bits and spreading code elements, the code elements are referred to as chips. The application of CDMA techniques improves standard optical heterodyne WDM system performance by increasing user capacity on a given WDM channel with minimal impact on system performance.

To illustrate the improvement realized by the application of CDMA techniques this work analyzes a nominal multiuser optical heterodyne FSK-CDMA system. System performance is measured by the probability of bit error as a function of the combined system laser linewidth, bit time product and the number of simultaneous users. Both receiver noise and multiuser noise are modeled as additive white Gaussian noise. For clarity, the receiver noise term is fixed at a given performance floor.

The next chapter provides a brief overview of available technology including associated advantages and disadvantages. Chapter III describes the noise terms which degrade system performance. Chapter IV describes the proposed OOK, FSK, and

FSK-CDMA systems, and Chapter V presents the mathematical analysis of the proposed systems with numerical results contained in chapter VI. Chapter VII provides conclusions and open problems.

II. SYSTEM COMPONENTS

All communications systems, including optical fiber systems, have a common structure. This chapter presents the various elements used by most optical fiber systems as well as the advantages and disadvantages of each.

A. THE TRANSMITTER

The optical source, or transmitter, is usually considered to be the active element in an optical fiber communications system. The primary purpose of the optical source is to convert an electrical signal into an optical signal which can be transmitted down an appropriate waveguide or fiber. The three main types of light sources available will now be discussed.

1. Wideband Sources

Although not widely used, wideband or continuous spectra sources such as incandescent lamps are available for use in optical fiber systems. Wideband sources are not adequate for most optical fiber communications schemes since they have an extremely slow response time, are difficult to control, and generate heat. Additionally, their excessively wide spectra make them totally unusable in coherent detection in which phase information is required to demodulate the received signal [Ref. 2].

2. Monochromatic Incoherent Sources

The next category of optical sources available are monochromatic incoherent sources, the most common of which is the light emitting diode (LED). As the name implies, the major advantage held by the LED over the incandescent source is the fact that its light is monochromatic. The reduced spectral width inherent to monochromatic light increases the frequency range over which the LED can be modulated. Further advantages of LEDs are [Ref. 1, 2]:

- Simpler fabrication
- Lower cost
- Reliability
- Little temperature dependence
- Simple drive circuitry
- Linear response region

The primary disadvantage to using LEDs in long haul communications schemes is the fact the output light is incoherent, that is; the light consists of photons with random phase. Incoherent light is less efficient in its transit through the fiber channel and as a result the transmitted signal tends to spread in time. This spreading, or dispersion, of the transmitted pulse has a direct effect on the maximum data rate supportable by the communications system. The wider the pulse becomes, the more time delay is needed between each successive pulse to prevent crosstalk. It is incoherency that makes the LED insufficient to support digital optical fiber communications systems requiring high signalling rates or long distance transmission [Ref. 2]. Other disadvantages of LED sources are their low power coupling capabilities, and harmonic distortion.

3. Monochromatic Coherent Sources

The final type of optical transmitter available for use is the monochromatic coherent source or laser. Early laser and fiber optic experiments were conducted using gas lasers, the only coherent light sources available. These devices provided extremely coherent light but were highly sensitive to mechanical shocks and vibrations and were very expensive. Gas lasers are also dangerous to personnel because of their high power output. The semiconductor injection laser, a small, lightweight, hardy, and inexpensive coherent light source is now available. As the term 'coherent' implies, the light emitted by lasers is monochromatic and in phase. Although these devices do not have zero spectral width, or linewidth, they are a significant improvement over incoherent LEDs. In addition to coherency, semiconductor lasers couple more of the emitted light into the fiber because of their highly directional emissions [Ref. 2]. Because of the nonlinear response of optical output to current input, semiconductor lasers are ideally suited to digital transmission schemes requiring high signalling rates or long distance transmissions.

The main disadvantages of semiconductor lasers are their unreliability and sensitivity to temperature. Semiconductor laser reliability is a key issue in fiber optics system design, as not all aspects of the failure mechanisms are fully understood [Ref. 2]. Laser failure mechanisms may be separated into two major categories known as 'catastrophic' and 'gradual' degradations. Catastrophic degradation results from mechanical damage to any of the laser surfaces resulting in either partial or total laser failure. Catastrophic degradation can be caused by the actual optical flux inherent to the device when operating in a pulsed mode. Gradual degradation results primarily from energy released by the nonradiative carrier recombination that occurs as a result of impurities in the semiconductor material which creates microscopic point defects on the reflective surfaces of the laser, fogging the reflective mirrors. Recent progress in the crystal fabrication of semiconductor lasers has resulted in a current mean laser lifetime of around 100 years [Ref. 2].

B. THE CHANNEL

There are two types of optical fibers available for use in optical fiber communications systems, single mode and multimode fibers. Each type of fiber will be discussed after basic common transmission degradation mechanisms are explored.

1. Common Degradations

There are several mechanisms which degrade fiber optic cable transmission performance. The severity of these degradations is primarily related to the transmission wavelength.

The first degradation common to both single mode and multimode fiber is material attenuation. Material attenuation is due to [Ref. 2]:

- Scattering of light by inherent inhomogeneities within the fiber
- Absorption of the light by impurities within the glass
- Connector losses
- Losses introduced by bends in the fiber

The effect of material attenuation is largely wavelength dependent, and longer wavelengths are attenuated less than shorter wavelengths.

A second physical mechanism that degrades fiber performance is Rayleigh scattering, which is intrinsic to the glass itself. Rayleigh scattering is the phenomenon by which molecules tend to interact more with higher frequency waves than lower frequency waves; hence, there is less attenuation at longer wavelengths than shorter ones. This is precisely the same reason the sky is blue. The net effect of Rayleigh scattering on system design is that it is more desirable to use longer wavelength light.

The upper limit on useable wavelength within the glass is due to an effect known as infrared absorption, a fundamental property of the glass fiber. Infrared absorption attenuates light at wavelengths greater than 1.6μ m [Ref. 1].

The final mechanism adversely affecting the transmission of light through all glass fiber is due to the presence hydroxyl radicals within the glass. These radicals tend to resonate at certain frequencies; hence, certain frequencies are less attenuated than others. Light with wavelengths centered about 850 nm, 1300 nm, and 1500 nm are the least attenuated by these radicals.

Due to these physical constraints, certain transmission limitations are imposed on system design by the properties inherent to the glass used to make the fiber. There is one property over which the system designer does have control, the fiber core diameter. This core diameter leads to the final aspect of channel transmission to be discussed, single mode and multimode fiber.

2. Multimode Fiber

Multimode fiber has a large core diameter and an improved transmitter coupling efficiency. Multimode fibers are generally cheaper to manufacture. The chief disadvantage of multimode fiber is that it readily admits light of different phase and frequency into the fiber which in turn leads to pulse spread and dispersion. Multimode fibers typically exhibit a loss of about 2 to 10 dB/km.

3. Single Mode Fiber

Single mode fibers are manufactured with extremely small core diameters, on the order of the wavelength of light, and are very delicate and expensive. Due to the small core size, it is exceptionally difficult to efficiently couple optical power into single mode fibers. The small core size is an asset, in that it restricts the frequency and phase of the transmitted light and suffers the least amount of dispersion and pulse spread of any of the manufactured fibers.

C. THE RECEIVER

The purpose of the receiver in optical fiber communications systems is to convert an optical signal to an electrical signal. In many respects, the receiver is the component in the system that limits maximum system performance. Key to detector performance are the following factors [Ref. 2]:

- High sensitivity at operating wavelengths
- High fidelity
- Large electrical response to received optical signal
- Short response time for maximum bandwidth
- Minimum noise introduced by the detector
- Stability of performance characteristics
- Small size
- High reliability
- Low cost

There are two devices which are currently used as detectors in optical fiber communications, and each will now be considered in greater detail.

1. The PIN Photodiode

The PIN photodiode is a semiconductor photodiode without internal gain. Incoming photons which impact the surface of the target area with sufficient energy will cause electrons weakly attached to the structure atoms to break free and enter the conduction band of the material. The movement of these free electrons produces an electric current. Ideally, each incoming photon should generate one electron-hole pair, but realistically, this is not the case [Ref. 2]. The measure of how well the material converts incoming photons to an electrical current is the quantum efficiency of the PIN photodiode and is expressed as a percentage of the number of electrons generated per number of incident photons. Typical values of quantum efficiency for modern PIN photodiodes is from 50 % to 75 % [Ref. 2]. The term PIN refers to the charge structure within the material.

2. The Avalanche Photodiode

The second major type of optical detector available for use in optical fiber communications is the avalanche photodiode (APD). The APD has a more sophisticated internal structure than the PIN photodiode, the purpose of which is to create an extremely high internal electric field. When an incoming photon is absorbed and frees an electron, the intense electric field causes the free electron to travel at speeds much higher than in normal devices. With this higher speed comes higher momentum and an increased probability that this electron will have sufficient energy to free other electrons from any atom it may collide with. This process is called impact ionization, and is the phenomenon which leads to avalanche breakdown in ordinary reverse biased diodes. The measure of the internal gain produced by the avalanche process is called the multiplication factor. Multiplication factors as high as 10^4 may be obtained using defect free materials [Ref. 2]. The avalanche effect is the primary advantage of the APD. Some disadvantages are:

- Slower response time than the PIN photodiode
- Asymmetrical electrical pulse at output
- Fabrication difficulties
- Increased cost

- High device operating voltages (100-400 V)
- Multiplication factor is temperature sensitive

This completes a brief overview of the existing optical communications system component technology. The integration of these components into the systems to be analyzed is described in Chapter IV. The next chapter mathematically quantifies the noise sources inherent to these components that impact system performance.

III. SOURCES OF NOISE

Detailed analysis of noise sources and their effect on communications systems is critical to the prediction and measurement of system performance. All communications systems are subject to degradation by noise whether natural, man-made, intentional, or unintentional. Before the analysis of specific system operation can be investigated, a summary of the inherent noise sources will be presented. The noise sources common to the OOK, FSK, and FSK-CDMA systems include laser phase noise in the transmitter and shot noise in the receiver. Multiuser noise is an additional Gaussian noise unique to the FSK-CDMA system.

A. TRANSMITTER NOISE

The semiconductor laser diode discussed in Chapter II may seem to be an ideal device for optical fiber communications; however, it is not without its problems. The major source of degradation to an optical fiber communication system is the laser phase noise. Laser phase noise is caused by randomly occurring spontaneous emission events, an inevitable aspect of laser operation [Ref. 3]. Each of these random events causes a sudden jump of phase in the electromagnetic field generated by the device. As time elapses, the phase of the laser executes a random walk away from its nominal value. The effect of this random walk in phase is to broaden the spectrum of the laser, giving it a non-zero spectral linewidth. As this linewidth increases, the range of frequencies over which the laser can be modulated decreases. As a result, the maximum achievable system bit rate decreases. It is the laser phase noise which sets the fundamental limit on the performance of coherent optical communications systems. Current laser diodes have linewidths from 10 kHz to 50 MHz [Ref. 3, 5]. By comparison, oscillators used in microwave communications systems have a linewidth on the order of 1 Hz [Ref. 3]. Laser linewidth also has a serious impact on many optical and electronic devices which extract timing and phase information from the incoming signal. As a result of the foregoing, there is substantial interest in decreasing the impact of laser linewidth.

Analysis of this random phase noise is extremely difficult. If the phase noise is modeled as a random walk process with the time between adjacent steps vanishingly small, the random phase becomes a Wiener process, characterized by a zero mean white Gaussian frequency noise spectrum with two sided spectral density N_0^l [Ref. 5]. The Wiener process assumption is valid for transmission frequencies greater than about 1 MHz [Ref. 3]. The power spectral density (PSD) of this process is the integral of the Gaussian function which is known as the Lorentzian lineshape and agrees with experimentally observed laser spectra [Ref. 9, 10]. The 3dB power points of the Lorentzian spectrum can be measured experimentally as the laser linewidth, β [Ref. 5]. In optical heterodyne systems, both the transmit and local lasers will add laser phase noise to the received signal. This will cause the introduction of a random frequency deviation to the IF signal related to the sum of the linewidths of the both lasers.

Simulation of the Lorentzian PSD is an extremely difficult and computationally intensive problem [Ref. 5] . In an attempt to simplify the problem, Chapter V of this thesis contains a compact, computationally efficient model for the random variable determined by the laser phase noise developed under a high user bit rate assumption. The high bit rate constraint assumes that the system signalling rate is high enough that the instantaneous frequency, while random from bit to bit, is constant over a bit interval. The high system signalling rate assumption is a key parameter of both the OOK and FSK systems. The validity of this assumption is shown in Chapter VI in which probability of bit error computations are presented using both the high bit rate phase noise model and a laser phase noise model obtained by other researchers [Ref. 11] that does not depend on the high bit rate assumption.

B. RECEIVER NOISE

The second common noise term degrading optical communication system performance is receiver noise. Receiver noise consists of shot noise generated by the photodetection process and thermal noise introduced by the electronic circuitry that follows the photodetector.

The shot noise in the receiver is due to the fact that light and electric current are defined by discrete carriers, photons and electrons, respectively. The discrete nature of light and electricity leads to a random fluctuation in the desired signal. The photodetector shot noise increases as the efficiency of the photodetector decreases. Thermal noise is shot noise generated by the resistive components in the receiver.

A shot noise process over a small number of events is characterized by a Poisson random process; however, heterodyne communication schemes add strong local oscillator power to the received signal, increasing the number of events in the shot noise process to the extent that the central limit theorem may be invoked [Ref. 1]. As a result, the total receiver noise term may be approximated as a zero mean white Gaussian random process with a two sided spectral density $N_0^s/2$.

Because one of the major advantages of optical heterodyne communications systems is the reduction of receiver shot noise, the chief effect of this noise on the system analysis presented in Chapter VI is to establish a lower limit on system probability of bit error performance.

C. MULTIUSER NOISE

Spread-spectrum code-division multiple access (CDMA) is an asynchronous multiple access communication scheme in which many users share a common bandwidth. In CDMA each user is assigned a particular code sequence which is used to modulate the carrier depending on the digital data [Ref. 6]. Under ideal conditions, each particular user code is orthogonal to every other user code, and as a result, invisible to other users. This is not the case in practical systems. A particular user recovers his coded bit stream through a receiver matched to the particular user's code. Other simultaneous user's signals will corrupt the received signal and appear as noise in the particular user's receiver. The mathematical representation of multiuser noise in CDMA systems has been the subject of extensive study. In many cases of interest, the multiuser noise is represented as a Gaussian random process. The Gaussian assumption loses validity when the spreading code length is low, less than three, the number of users is low, less than about two, and the signal-to-noise ratio is large, greater than about 12 dB [Ref. 12]. CDMA is specifically implemented in the proposed optical FSK-CDMA communication system to maximize the multiuser capacity, and consequently the Gaussian model for the multiuser noise is valid. The validity of the Gaussian multiuser noise model degrades at lower code lengths and fewer numbers of users, but for small numbers of users the laser phase noise will dominates system performance.

The analysis conducted in Chapter V considers CDMA implementation of both random signature sequences and Gold code sequences. Random signature sequences are constructed of a sequence of random variables taking values $\{+1, -1\}$ with equal probability, and all sequences are mutually independent. Analysis using random signature sequences is mathematically simpler, but purely random signature sequences are not implemented in actual systems. Gold code sequences are not random sequences but pseudorandom sequences and are constructed from two maximal length sequences. Gold codes are designed to give random signature sequence performance, and previous work in the field indicates that the results obtained using random signature sequences accurately model the implementation of actual Gold codes [Ref. 13]. Probability of bit error computations conducted in Chapter VI verify this assumption.

A detailed description of both systems under analysis is presented in the next chapter and noise terms described in this chapter will be incorporated into the system analysis presented in Chapters V and VI.

IV. SYSTEM DESCRIPTION

This chapter describes the coherent optical heterodyne OOK system, the coherent optical heterodyne FSK system, and the proposed coherent optical heterodyne FSK-CDMA system to be analyzed in this thesis. Each section describes system operation and the components considered in the mathematical analysis.

A. ON-OFF KEYING

This section describes an optical heterodyne OOK communications system with noncoherent detection. A block diagram of this system is shown in Figure 4.1. It is assumed that the user bit stream consists of a mutually independent random series of 'ones' and 'zeros'. The system will only transmit a signal when the user has data to send, otherwise the station will remain idle. In the transmitter, the user data stream OOK modulates a semiconductor laser. If the bit is a 'one', the laser transmits an optical pulse of duration T_b seconds, and if the bit is a 'zero' no pulse is transmitted over the bit interval. At the receiver, the system mixes a locally generated optical signal with the incoming optical signal. The combined signal is then detected by a photodetector. The local optical signal is generated by a semiconductor laser tuned to a frequency approximately 10^9 Hz from the transmit laser. As with its electromagnetic analog, this optical heterodyne process creates sum and difference frequencies. The sum frequencies are filtered out and the difference frequencies, in the microwave range, are detected by a photodetector. This detection transforms the optical OOK signal into an electrical OOK signal at an intermediate frequency (IF). The optical heterodyne process can be accomplished with a beam splitter [Ref. 5], and the proposed system uses a standard PIN photodetector as described in Chapter

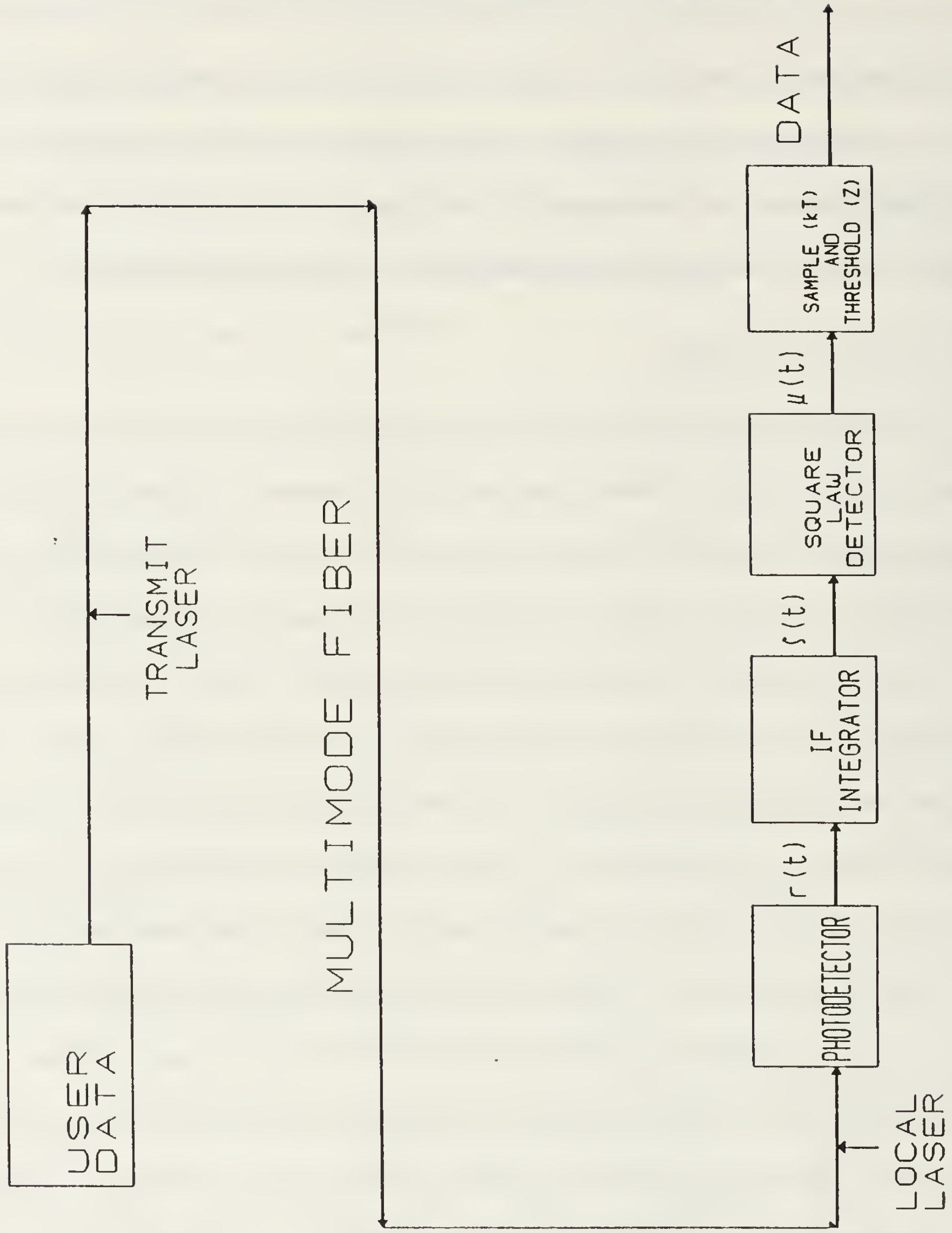

Figure 4.1: Optical Heterodyne OOK System

II. A standard PIN photodetector is used vice an avalanche photodetector because the received signal is a high speed OOK signal and the avalanche photodetector has a slower response than the PIN photodetector and exhibits non-linear characteristics. The electrical OOK signal is transmitted through an ideal finite time bandpass integrator with an integration time T_b. The filtered signal is then noncoherently demodulated by a square law detector, and the user bit stream is recovered by a threshold device normalized to the bit energy.

B. FREQUENCY SHIFT KEYING

This section describes the operation and components of an optical heterodyne binary FSK system with noncoherent detection. A diagram of the receiver is shown in Figure 4.2. It is assumed that the user bit stream consists of a mutually independent random series of 'ones' and 'zeros'. The system will only transmit a signal when the user has data to send, otherwise the station will remain idle. Each transmitter FSK modulates a semiconductor laser diode with the user bit stream. In the case of a bit 'one', an optical signal at frequency f_1 is transmitted. In the case of a bit 'zero', an optical signal at frequency f_0 is transmitted. It is assumed that f_1 and f_0 are sufficiently separated in frequency that there is negligible interference between the two FSK tones. The receiver structure for noncoherent FSK detection is very similar to noncoherent OOK detection. Each receiver actually consists of two separate receivers, called branches. One branch is matched to f_1 and the other is matched to f_0. Each branch of the user's receiver mixes a locally generated optical signal with the incoming optical signal and then detects the difference frequencies with a photodetector. The resulting electrical signal is then integrated over the bit interval and sampled at the bit time. The signal is then noncoherently demodulated by a square law detector. The output of the square law detector is input to a comparator for bit recovery. The

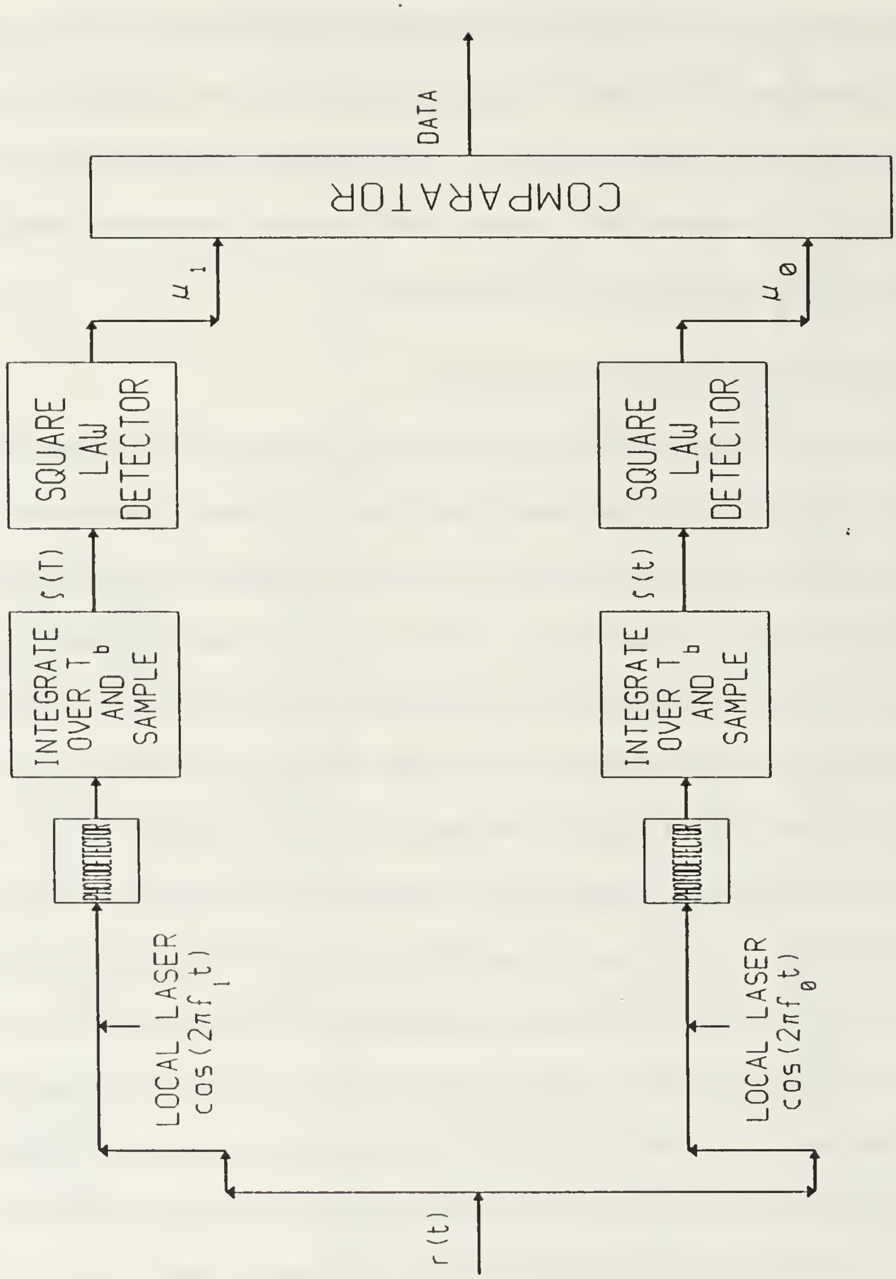

Figure 4.2: Optical Heterodyne FSK Receiver

comparator is simply a threshold device with the threshold set at zero. As with the OOK system, this FSK system uses semiconductor laser diodes for their high speed performance, multimode fiber for transmission, and a PIN photodiode for its high speed performance as discussed in Chapter II.

C. FREQUENCY SHIFT KEYING CODE-DIVISION MULTIPLE ACCESS

The proposed FSK-CDMA system operates in the same manner and with the same components as the basic FSK system. A diagram of the receiver is shown in Figure 4.3. The major operational differences between the basic FSK system and the FSK-CDMA system will now be explained. After the user bit stream FSK modulates the transmit laser, the transmitter encodes the FSK bit stream into the spreading sequence through binary amplitude modulation producing a high frequency chip stream consisting of two frequencies, each phase modulated with the user code sequence. The transmitted signal is then optically mixed with other transmitter signals in the common optical fiber channel. The proposed system uses multimode fiber to accommodate the large number of possible system users. The system under consideration is also considered to be a 'power balanced network'. In this type of network every signal, desired or undesired, is transmitted with the same power [Ref. 8].

The FSK-CDMA receiver is more complicated than the standard FSK receiver. Each of the frequency matched receivers consists of two branches in quadrature. Each branch of the user's receiver adds a locally generated optical signal to the incoming composite optical signal and then detects the sum with a photodetector. A significant difference between the FSK-CDMA receiver and the FSK receiver is the fact that the locally generated optical signal added to the incoming signal is phase modulated with

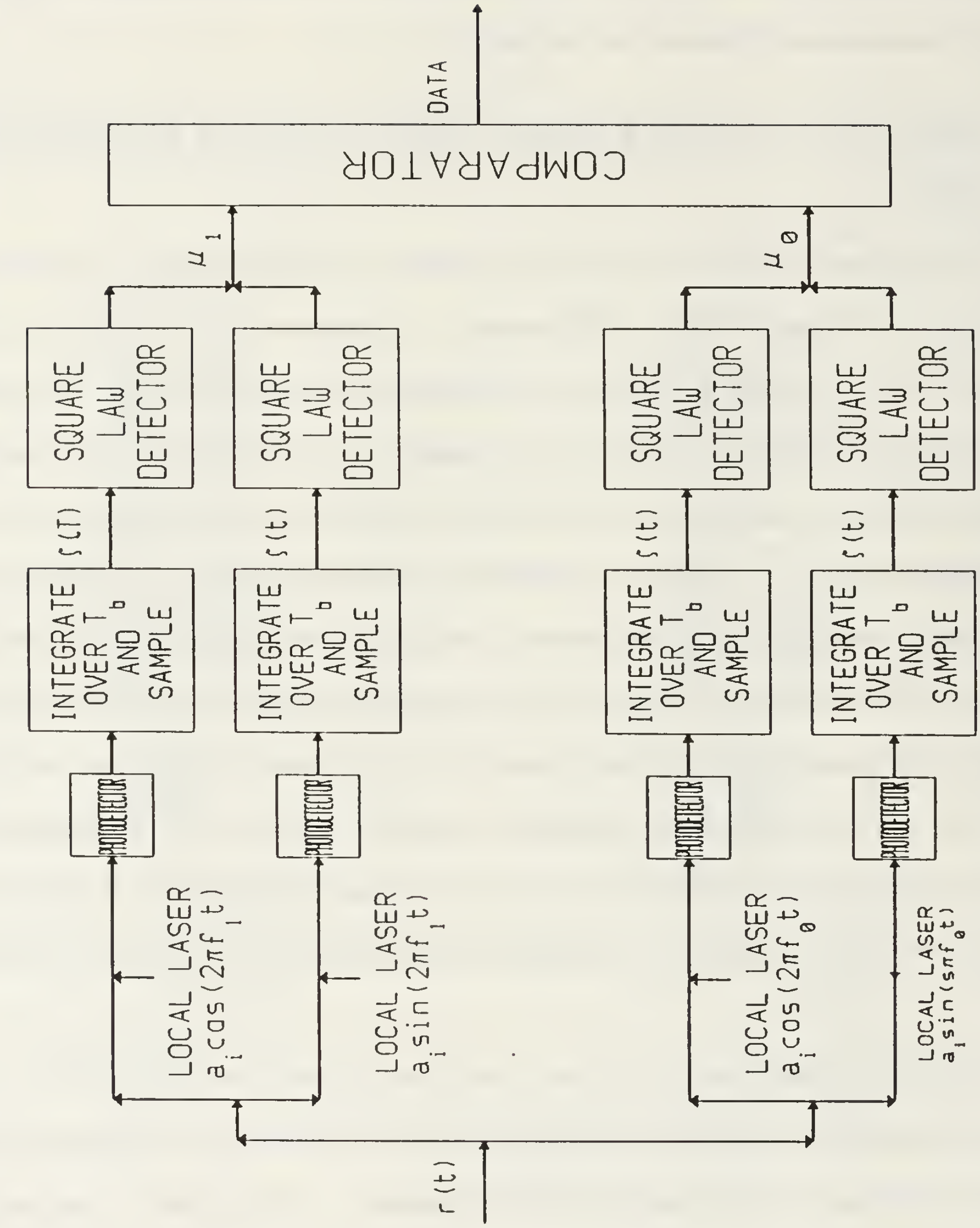
DATA
COMPARATOR
μ 1
μ 0
SQUARE LAW DETECTOR
SQUARE LAW DETECTOR
SQUARE LAW DETECTOR
SQUARE LAW DETECTOR
s(t)
s(t)
s(t)
s(t)
INTEGRATE OVER T b AND SAMPLE
INTEGRATE OVER T b AND SAMPLE
INTEGRATE OVER T b AND SAMPLE
INTEGRATE OVER T b AND SAMPLE
PHOTODETECTOR
PHOTODETECTOR
PHOTODETECTOR
PHOTODETECTOR
LOCAL LASER a i cos(2πf 1 t)
LOCAL LASER a i sin(2πf 1 t)
LOCAL LASER a i cos(2πf 0 t)
LOCAL LASER a i sin(sπf 0 t)
r(t)

Figure 4.3: Optical Heterodyne FSK-CDMA Receiver

the user code sequence. The resulting electrical signal is then integrated over the bit interval and noncoherently demodulated by a square law detector. The output of each square law detector is then added to its quadrature component to form the correlation statistics. The correlation statistics produced by each of the two frequency matched branches are then input to a comparator for bit recovery. As with standard FSK systems, the comparator is a threshold device with the threshold set at zero.

The specifics of the optical heterodyne systems are now defined and the next chapter will present the numerical analysis of these systems.

V. MATHEMATICAL ANALYSIS

This mathematical analysis chapter presents the derivation of the probability of bit error for the the OOK, FSK, and FSK-CDMA systems described in Chapter IV.

A. ON-OFF KEYING

The performance of the optical heterodyne OOK system shown in Figure 4.1 will be degraded by laser phase noise and shot noise introduced at the receiver. The analysis thus requires the statistics of the output waveform $\mu(T)$ of the square law detector corrupted by laser phase noise and receiver shot noise as well as the statistics of the normalized samples $z_k = \mu(kT_b)$ at the threshold. If Z is the normalized decision threshold, then the probability of bit error is

$$P_b = 0.5[P_0(Z) + P_1(Z)] \tag{5.1}$$

where

$$P_0(Z) = \int_Z^\infty p(\mu \mid 0) d\mu \tag{5.2}$$

and

$$P_1(Z) = \int_0^Z p(\mu \mid 1) d\mu \tag{5.3}$$

where $P_0(Z)$ is the probability of making an error when a 'zero' is sent, $P_1(Z)$ is the probability of making an error when a 'one' is sent, $p(\mu \mid 0)$ is the decision statistic at the input of the sample and threshold device when a 'zero' is transmitted, and $p(\mu \mid 1)$ is the decision statistic at the input of the sample and threshold device when a 'one' is transmitted. Equally likely signalling is assumed.

The analysis begins with the derivation of the conditional probability density functions (pdf) for the decision variable based on the signal input to the threshold device. The mathematical expressions to represent the pdf of the magnitude of the random variable produced by the laser phase noise are then derived and the analysis concludes with the analytic evaluation of 5.2 and 5.3.

1. Conditional Probability Density Functions of the Decision Variable Z_K.

In the following analysis, R_b represents the user bit rate and $T_b = 1/R_b$ represents the user bit interval. In the OOK transmission scheme described, the user bit stream modulates a semi-conductor laser diode, sending one of two signals every T_b second interval: a pulse of optical energy in the case of a 'one', and nothing in the case of a 'zero' [Ref. 5]. At the receiver, the signal is mixed with a local oscillator and detected by a photodetector to produce the system IF input. Using complex envelope notation, the IF waveform at each T_b interval can be represented as

$$r(t) = \begin{cases} S\exp\left[j\theta(t)\right] + n(t) & \text{Data=1} \\ n(t) & \text{Data=0} \end{cases} \tag{5.4}$$

where S^2 is the power received in the optical pulse, $\theta(t)$ is the composite phase noise due to both the transmitting and receiving lasers, and $n(t)$ is the complex receiver noise. As shown in Figure 4.1, the received signal $r(t)$ is input to an ideal passband integrator with an integration time T_b. The integrator output $\zeta(t)$ is then detected by an ideal square law detector whose baseband output is related to its input by $\mu(t) = \mid \zeta(t) \mid^2$ [Ref. 5]. The ideal square-law detector output $\mu(t)$ is then sampled at time intervals of T_b providing the decision variable

$$z_k = \mu(kT_b) \tag{5.5}$$

Finally, z_k is compared against a normalized threshold Z to determine whether a 'one' or a 'zero' was sent. For this analysis, maximum likelihood detection is assumed. The bit interval is considered over $k = 1$, and for clarity the subscript on the decision variable z_k is dropped.

From the above discussion, at a given time T, the IF filter response is

$$\zeta(T) = \begin{cases} \frac{S}{T_b}\int_0^{T_b} \exp\left[j\theta(t)\right] dt + \hat{n} & \text{Data=1} \\ \hat{n} & \text{Data=0} \end{cases} \tag{5.6}$$

where $\hat{n}$ is the zero mean additive white Gaussian receiver noise sample with a total variance $\sigma^2 = N_0/2T$ [Ref. 5]. The nature and expression for the random sample of the laser phase noise probability density function (pdf) will be derived later. The receiver noise is an additive white Gaussian random variable consisting of quantum noise, background light noise, dark current noise and thermal noise. Due to the strong local oscillator condition discussed in Chapter III, these noise sources are approximated as Gaussian random processes [Ref. 14]. The additive receiver noise term is thus a zero mean Gaussian random variable with variance $N_0/2T$.

When the data sent is a zero, the conditional pdf of the decision variable is [Ref. 5, 15]

$$p(\mu \mid 0) = \frac{1}{\sigma^2}\exp\left(-\frac{\mu}{\sigma^2}\right) \tag{5.7}$$

The analysis is a little more difficult when a one is sent. In 5.6, the signal power S is fixed, n is a random Gaussian variable with known variance, and the laser phase noise is governed by the phase noise process $\theta(T_b)$. If the random variable X is defined as

$$X = \left| \frac{1}{T_b}\int_0^{T_b} \exp\left[j\theta(t)\right] dt \right| \tag{5.8}$$

then the pdf of the decision variable conditioned on x is given as the envelope squared of a sinusoid plus narrow-band Gaussian noise [Ref. 5, 15] as

$$p(\mu \mid 1, x) = \frac{1}{\sigma^2}\exp\left(-\frac{\mu + S^2x^2}{\sigma^2}\right) I_0\left(\frac{2Sx\sqrt{\mu}}{\sigma^2}\right) \tag{5.9}$$

where $I_0(\bullet)$ represents the modified Bessel function of zero order. The pdf of the decision variable when a 'one' is sent is

$$p(\mu \mid 1) = \int_0^1 p(\mu \mid 1, x) p_X(x) dx \tag{5.10}$$

where $p_X(x)$ is the pdf of the random variable X which is determined by the laser phase noise and the bit rate. Having determined the conditional probability density functions of the decision random variable, an expression for the pdf of the random variable X will now be derived.

2. Probability Density Function of the Laser Phase Noise Variate

Due to the filter response of the initial IF filter, the pdf of the random variable X depends strictly upon the laser linewidth β and the bit rate T_b. Direct evaluation of this pdf is computationally intensive since $\theta(t)$ in 5.4 is a Brownian motion process. Past works have numerically evaluated this pdf through numerical integration and Monte Carlo simulation, and report that large amounts of computational time are required [Ref. 5]. Attempts to simplify the analysis of the probability of bit error in lightwave systems corrupted by laser phase noise through the derivation of a closed form analytical model representing the pdf of X has resulted in a curve fit approximation of the actual pdf. For an integrate and dump filter the pdf of the random variable X determined by the laser phase noise is approximated as [Ref. 11]

$$p_X(x) = \begin{cases} \alpha \exp\left[-\alpha(1-x)\right] & 0 \leq x \leq 1 \\ 0 & \text{otherwise} \end{cases} \tag{5.11}$$

where

$$\alpha = \frac{1.6}{\beta T_b}\left(1 + 0.5\sqrt{\beta T_b}\right) \tag{5.12}$$

The accuracy of this model has been demonstrated over many different system signalling rates [Ref. 5]. This expression will be used as a baseline to check the range of validity of the expression for the pdf of the random variable X determined by the laser phase noise to be subsequently derived.

In optical communications systems laser phase noise has the greatest impact on systems with low signalling rates. In the OOK system under investigation the bit rate is sufficiently high that the frequency deviation from one bit interval to the next bit interval is random, but constant over the bit interval. This assumption implies $\theta(t) = \omega t = 2\pi\beta t$ in 5.4, and the value of the random variable at the output of the IF filter given by 5.8 is evaluated to obtain

$$X = \left| \operatorname{sinc}\left(\frac{\omega T_b}{2}\right) \right| \approx 1 - \frac{\left(\frac{\omega T_b}{2}\right)^2}{3!} \tag{5.13}$$

where the approximation is valid for small values of βT_b. This approximate non-linear relationship between the random variables X and ωT_b is used to obtain

$$p_X(x) \approx \sqrt{\frac{3}{2(1-x)}} \left\{ p_{\frac{\omega T_b}{2}}\left[\sqrt{6(1-x)}\right] + p_{\frac{\omega T_b}{2}}\left[-\sqrt{6(1-x)}\right] \right\} \tag{5.14}$$

where $p_{\frac{\omega T_b}{2}}(\bullet)$ is the pdf of the phase noise process for a given laser linewidth, in radians, over the bit interval. The general pdf for the phase fluctuation over a given measurement time is [Ref. 10]

$$p_\theta(\theta) = \frac{1}{\sqrt{4\pi^2 \beta T_b}} \exp\left(-\frac{\theta^2}{4\pi\beta T_b}\right) \tag{5.15}$$

For a phase fluctuation that is constant over a bit interval, $\omega = \frac{\theta}{T_b}$. Making the appropriate change of variables in 5.15, one gets

$$p_{\frac{\omega T_b}{2}}\left(\frac{\omega T_b}{2}\right) = \frac{1}{\sqrt{\pi^2 \beta T_b}} \exp\left[-\frac{\left(\frac{\omega T_b}{2}\right)^2}{\pi\beta T_b}\right] \tag{5.16}$$

Substituting 5.16 into 5.14 one obtains

$$p_X(x) \approx \sqrt{\frac{6}{\pi^2 \beta T_b (1-x)}} \exp\left[-\frac{6(1-x)}{\pi\beta T_b}\right] \tag{5.17}$$

This equation is valid for $1/T_b \gg \beta$. In the numerical analysis conducted in Chapter VI, the range of validity of this assumption will be investigated.

3. Analytical Simplification of the Probability of Bit Error Expression

The computation of the probability of bit error requires evaluation of 5.1, the sum of the probabilities of making an incorrect decision for both a transmitted ‘one’ and ‘zero’. The probability of making an incorrect decision when a ‘zero’ is transmitted can be found by integrating 5.7 over the incorrect decision region which simply gives

$$P_0(Z) = \int_Z^\infty \frac{1}{\sigma^2} \exp\left(-\frac{\mu}{\sigma^2}\right) d\mu = \exp\left(-\frac{Z}{\sigma^2}\right) \tag{5.18}$$

where Z is the normalized threshold setting and σ^2 is the variance of the additive white Gaussian noise.

Computation of the probability of making an incorrect decision for a transmitted ‘one’ is significantly more difficult because it requires integrating 5.10 over the incorrect decision region to yield the double integral

$$P_1(Z) = \int_0^Z \int_0^1 p(\mu \mid 1, x) p_X(x) dx d\mu \tag{5.19}$$

The double integral in 5.19 is reduced to a single integral as follows. Both expressions for the pdf of $p_X(x)$ given by 5.11 and 5.17 are independent of μ. Hence

$$P_1(Z \mid X) = \int_0^Z p(\mu \mid 1, x) d\mu = \int_0^Z \frac{1}{\sigma^2} \exp\left(-\frac{\mu + S^2x^2}{\sigma^2}\right) I_0\left(\frac{2Sx\sqrt{\mu}}{\sigma^2}\right) d\mu \tag{5.20}$$

where $I_0(\bullet)$ is the modified Bessel function of zero order and

$$I_0(y) = \sum_{n=0}^{\infty} \frac{\left(\frac{y^2}{4}\right)^n}{n!\Gamma(n+1)} \tag{5.21}$$

Substituting the argument of $I_0(\bullet)$ in 5.20, one gets

$$I_0\left(\frac{2Sx\sqrt{\mu}}{\sigma^2}\right) = \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left[\frac{S^2x^2\mu}{\sigma^4}\right]^n \tag{5.22}$$

Interchanging the order of integration and summation and substituting 5.22 into 5.20, one obtains

$$P_1(Z \mid x) = \left[\sum_{n=0}^{\infty} \frac{1}{\sigma^2 (n!)^2} \left(\frac{S^2x^2}{\sigma^4}\right)^n \int_0^Z \mu^n \exp\left(-\frac{\mu}{\sigma^2}\right) d\mu\right] \exp\left(-\frac{S^2x^2}{\sigma^2}\right) \tag{5.23}$$

which can be evaluated to yield

$$P_1(Z \mid x) = \exp\left(-\frac{S^2x^2}{\sigma^2}\right) \sum_{n=0}^{\infty} \frac{1}{(n!)} \left(\frac{S^2x^2}{\sigma^2}\right)^n \left[1 - \exp\left(-\frac{Z}{\sigma^2}\right) \sum_{r=0}^{n} \frac{1}{(n-r)!} \left(\frac{Z}{\sigma^2}\right)^{n-r}\right] \tag{5.24}$$

using 5.24 the computationally efficient expression for the error probability in the case of a transmitted ‘one’ is

$$P_1(Z) = \int_0^1 P_1(Z \mid x) p_X(x) dx \tag{5.25}$$

where now only a single numerical integration is required. Numerical evaluation of 5.25 requires truncation of the infinite series in 5.24. The dominant term controlling series convergence is $\left(\frac{S^2x^2}{\sigma^2}\right)$. The series converges rapidly for small arguments. Since S^2 is a constant, convergence depends on x^2 and σ^2. Over the range of integration, x^2 varies from zero to one, and σ^2 depends on the additive white Gaussian receiver noise. As a result, the number of terms retained in the series is controlled by an adaptive process based on the SNR and the value of x.

B. FREQUENCY SHIFT KEYING

Derivation of the probability of bit error for the FSK receiver shown in Figure 4.2 proceeds in a manner similar to that for the OOK system analysis. System performance will be degraded by laser phase noise and shot noise introduced at the receiver. As before, the analysis requires the statistics of the output wave form $\mu_i(T)$, $i = 0, 1$ of the square law detector corrupted by laser phase noise and receiver shot noise as well as the statistics of the normalized samples $z_{ik} = \mu(kT_b)$ at the output of the square law detector for each of the two frequency matched branches.

In the case of FSK, the decision threshold, Z is zero. The probability of bit error is

$$P_b = 0.5[P_0(E) + P_1(E)] \tag{5.26}$$

where

$$P_0(E) = \int_0^{\infty} p(\mu_0 \mid 0) d\mu_0 \tag{5.27}$$

and

$$P_1(E) = \int_0^{-\infty} p(\mu_1 \mid 1) d\mu_1 \tag{5.28}$$

where $P_0(E)$ is the probability of making an error when a 'zero' is sent, $P_1(E)$ is the probability of making an error when a 'one' is sent, $p(\mu_0 \mid 0)$ is the decision statistic at the input of the comparator when a 'zero' is transmitted, and $p(\mu_1 \mid 1)$ is the decision statistic at the input of the comparator when a 'one' is transmitted.

The analysis begins with the derivation of 5.27 and 5.28, the conditional probability density functions for the decision variable based on the signal input to the comparator. The analysis then concludes with the analytic evaluation of 5.27 and 5.28.

1. Derivation of the Conditional Probability of Bit Error

Due to the symmetry of the FSK receiver shown in Figure 4.2, the probability of making an error is the same for both a transmitted 'one' and transmitted 'zero'; that is, $P_1(E) = P_0(E)$. Because of this symmetry, only one branch of the receiver needs to be analyzed. The signal is, therefore, assumed to be present in the upper branch of the receiver shown in Figure 4.2. If it is assumed that a user bit 'one' is sent on frequency f_1, then for the receiver branch matched to frequency f_1, the input to the square law detector is

$$\zeta_1(T) = \begin{cases} \frac{S}{T_b} \int_0^{T_b} \exp\left[j\theta(t)\right] dt + \hat{n} & \text{Data=1} \\ \hat{n} & \text{Data=0} \end{cases} \tag{5.29}$$

where $\hat{n}$ is a zero mean additive white Gaussian receiver noise sample with a total variance $\sigma^2 = N_0/2T_b$. For a given value of the square law detector output, μ_1, an error is made if $\mu_0 > \mu_1$. For this FSK system, the conditional error probability is

$$P_1(E \mid \mu_1) = \int_{\mu_1}^{\infty} p\,(\mu_0 \mid 1)\, d\mu_0 \tag{5.30}$$

where $p\,(\mu_0 \mid 1)$ is the pdf for μ_0 when a data bit 'one' is sent. This density function is identical to that for OOK when a data bit 'zero' is sent and is given by

$$p\,(\mu_0 \mid 1) = \frac{1}{\sigma^2} \exp\left(-\frac{\mu_0}{\sigma^2}\right) \tag{5.31}$$

The average error probability is obtained by averaging over all values of μ_1 to get

$$P_b = \int_0^{\infty} P_1(E \mid \mu_1) p\,(\mu_1 \mid 1, x)\, d\mu_1 \tag{5.32}$$

As with OOK, $p\,(\mu_1 \mid 1, x)$ is given as the envelope squared of a sinusoid plus narrowband Gaussian noise conditioned on X [Ref. 15]

$$p(\mu_1 \mid 1, x) = \frac{1}{\sigma^2} \exp\left(-\frac{\mu_1 + S^2x^2}{\sigma^2}\right) I_0\left(\frac{2Sx\sqrt{\mu_1}}{\sigma^2}\right) \tag{5.33}$$

where $I_0(\bullet)$ represents the modified Bessel function of zero order. The pdf of the decision variable when a 'one' is sent is

$$p\,(\mu_1 \mid 1) = \int_0^1 p\,(\mu_1 \mid 1, x)\, p_X(x) dx \tag{5.34}$$

where $p_X(x)$ is the pdf for the random quantity X. The total probability of bit error is thus

$$P_b = \int_0^{\infty} p\,(\mu_1 \mid 1) \left[\int_{\mu_1}^{\infty} p\,(\mu_0 \mid 1)\, d\mu_0\right] d\mu_1 \tag{5.35}$$

The expression for the probability of bit error is be simplified in the next section.

2. Analytical Simplification of the Probability of Bit Error Expression

The simplification of 5.35 proceeds as follows. The conditional error probability given in 5.30 can be integrated to obtain

$$P_1(E \mid \mu_1) = \int_{\mu_1}^{\infty} p(\mu_0 \mid 1)\, d\mu_0 = \exp\left(-\frac{\mu_1}{\sigma^2}\right) \tag{5.36}$$

Combining 5.9 - 5.36 one gets

$$P_b = \int_0^1 \int_0^\infty \frac{1}{\sigma^2} \exp\left(-\frac{2\mu_1 + S^2x^2}{\sigma^2}\right) I_0\left(\frac{2Sx\sqrt{\mu_1}}{\sigma^2}\right) p_X(x) d\mu_1 dx \tag{5.37}$$

Using the identity

$$I_0\left(\frac{2Sx\sqrt{\mu_1}}{\sigma^2}\right) = \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left[\frac{S^2x^2\mu_1}{\sigma^4}\right]^n \tag{5.38}$$

P_b becomes

$$P_b = \int_0^1 \int_0^\infty \frac{1}{\sigma^2} \exp\left(-\frac{2\mu_1 + S^2x^2}{\sigma^2}\right) \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left[\frac{S^2x^2\mu_1}{\sigma^4}\right]^n p_X(x) d\mu_1 dx \tag{5.39}$$

Rearranging 5.39 one gets,

$$P_b = \int_0^1 \frac{\exp\left(-\frac{S^2x^2}{\sigma^2}\right)}{\sigma^2} \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left[\frac{S^2x^2}{\sigma^4}\right]^n p_X(x) \int_0^\infty \mu_1^n \exp\left(-\frac{2\mu_1}{\sigma^2}\right) d\mu_1 dx \tag{5.40}$$

Using the definite integral

$$\int_0^\infty \mu_1^n \exp\left(-\frac{2\mu_1}{\sigma^2}\right) d\mu_1 = \frac{n!}{\left(\frac{2}{\sigma^2}\right)^{n+1}} \tag{5.41}$$

P_b is reduced to

$$P_b = \int_0^1 \frac{\exp\left(-\frac{S^2x^2}{\sigma^2}\right)}{2} \sum_{n=0}^{\infty} \frac{1}{(n!)} \left[\frac{S^2x^2}{2\sigma^2}\right]^n p_X(x) dx \tag{5.42}$$

Since

$$\sum_{n=0}^{\infty} \frac{1}{(n!)} \left[\frac{S^2x^2}{2\sigma^2}\right]^n = \exp\left(\frac{S^2x^2}{2\sigma^2}\right) \tag{5.43}$$

P_b can be simplified to

$$P_b = \int_0^1 \frac{\exp\left(-\frac{S^2x^2}{2\sigma^2}\right)}{2} p_X(x) dx \tag{5.44}$$

which now must be evaluated numerically.

C. FREQUENCY SHIFT KEYING CODE-DIVISION MULTIPLE ACCESS

The probability of bit error expressions for the FSK-CDMA receiver shown in Figure 4.3 are essentially the same as those for the FSK receiver derived in the previous section. The difference is that the noise term n now includes additive white Gaussian multiuser noise. This section presents the mean and variance of the various additive white Gaussian noise terms present in the FSK-CDMA system. In the following subsections, K represents the number of users and N represents the number of chips in the spreading code.

1. Multiuser noise

The representation of multiuser noise in CDMA systems as a Gaussian random variable has been the subject of extensive study. As discussed in Chapter III, the Gaussian assumption is valid for this application. In this analysis, both random codes and Gold codes are employed.

a. Random Codes

Much work has been done in recent years to characterize the statistics of direct-sequence spread-spectrum codes. The difficulty in analyzing such systems is the fact that they are asynchronous and proper analysis requires characterizing not only the periodic but also the aperiodic cross-correlation properties. Most current models treat phase shifts, time delays, and data symbols as mutually independent random variables. The multiuser interference terms are treated as additional random noise. Such assumptions are considered valid for multiuser systems with long code lengths [Ref. 6, 16]. The Gaussian random variable that describes the multiuser noise for random codes is zero mean with a variance [Ref. 6, 7]

$$\sigma^2 = \frac{S^2 T_b^2 (K-1)}{6N} + \frac{N_0^s T_b}{4} \tag{5.45}$$

where $N_0^s/2$ is the two sided spectral density of the additive white Gaussian receiver noise.

b. Gold Codes

Computation of the statistics governing Gold codes is a rigorous process, and most results require the use of approximations to generate a useable result. One characteristic of Gold codes is the fact that the periodic cross-correlation between two sequences takes on discrete values related to the code length N. Previous work approximates the Gaussian statistics of Gold codes as zero mean with a variance [Ref. 8]

$$\sigma^2 = \left(\frac{K-1}{N}\right)\left(N^2 + N - 1\right) \tag{5.46}$$

Researchers have also shown that an acceptable approximation for the asynchronous cross-correlation factor for rectangular chip types is 1/3 [Ref. 7]. Substituting the synchronous expression given by 5.46 into the asynchronous expression given by 5.45 and including the cross-correlation factor, one obtains the Gaussian random variable modelling Gold coded multiuser noise as zero mean with an approximate variance

$$\sigma^2 = \frac{(N^2 + N - 1)(K-1)}{6N} + \frac{N_0^s T}{4} \tag{5.47}$$

where $N_0^s/2$ is the two sided spectral density of the additive white Gaussian receiver noise. The similarity between 5.45 and 5.47 is noted, and it is expected that system performance will be slightly degraded when Gold codes are used instead of random codes.

2. Receiver noise

The receiver noise is an additive white Gaussian random variable consisting of quantum noise, background light noise, dark current noise, and thermal noise. Due to the strong local oscillator condition discussed in Chapter III, these noise sources are accurately approximated as Gaussian random processes [Ref. 14]. The additive receiver noise term is modeled as a zero mean Gaussian random variable with variance $N_0^s/2$.

All expressions for the various probabilities of bit error discussed in this chapter are be used in the next chapter to numerically analyze the performance of the various systems over parameters of interest.

VI. NUMERICAL RESULTS

The numerical analysis requires the evaluation of 5.1 for the single user OOK system and 5.26 for the FSK and multiuser FSK-CDMA systems. The numerical simulations were conducted in the Matlab environment and on a 386 based personal computer running at 33 MHz with a Weitek accelerator.

A. ON-OFF KEYING

Computation of the probability of bit error for OOK involves a numerical evaluation of 5.1 for different user bit rates over various system signal-to-noise ratios (SNR). The SNR is the ratio of the signal power to the additive white Gaussian noise power. In addition, 5.1 is evaluated for each of the two probability density functions representing effect of the laser phase noise on system performance given by 5.11 and 5.17. The impact of the threshold setting Z on system performance is also explored. The threshold level is of interest because previous analysis of OOK systems corrupted by laser phase noise indicates an optimum normalized threshold level setting at $Z \approx 0.3$ [Ref. 10, 5], while standard analysis of communications systems corrupted by additive white Gaussian noise indicates an optimum normalized threshold setting at $Z \approx 0.5$ when SNR is large [Ref. 4]. Analysis of the ideal normalized threshold level indicates which noise source, Gaussian noise or laser phase noise, dominates system performance.

For clarity and ease of analysis the maximum receiver SNR is numerically fixed at 19 dB. This results in a probability of bit error floor of 10^{-9} when additive white Gaussian noise is the only source of interference. The user bit rate is expressed in terms of the laser linewidth so that system performance for different values of βT_b may be studied. The resulting curves are expressed in terms of βT_b because this allows a generalized application of the results presented in this thesis. It is also assumed that the optical signal power of each individual user is normalized to unity.

1. System SNR Performance

Initially the normalized threshold is set at 0.3 for values of βT_b from $1/2^1$ to $1/2^9$ over varying values of SNR using the curve fit approximation for $p_X(x)$ given by 5.11. The resulting curves are shown in Figures 6.1-6.3. As expected, increased bit rates, implying lower βT_b, reduce the impact of laser phase noise on the probability of bit error. As the system SNR decreases, the probability of bit error performance degrades in the same manner for all systems. These curves also illustrate that optimum system performance can be obtained with a user bit rate approximately 10 times the laser linewidth; that is, $\beta T_b \leq 0.1$ [Ref. 3, 5].

2. Normalized Threshold Setting

The second aspect of system performance to be investigated is the optimal normalized threshold setting Z. As discussed earlier, standard communications systems degraded by additive white Gaussian noise exhibit optimal performance at a normalized threshold setting of about 0.5 for large SNR. The system under investigation is not only degraded by additive white Gaussian noise but also by laser phase noise. Investigations of systems degraded by laser phase noise indicate the optimal threshold setting is approximately 0.3 [Ref. 5]. Numerical results were computed for the system under the previously stated assumptions except the normalized threshold is set at 0.5. The results are shown in Figures 6.4-6.6. Comparison of Figures 6.4-6.6 with Figures 6.1-6.3 illustrates the fact that a normalized threshold of around 0.3 yields better overall performance than a threshold of 0.5.

Finally, system performance for different normalized threshold levels is investigated. For a nominal case, $\beta T_b = 1/128$ is chosen with all previous assumptions

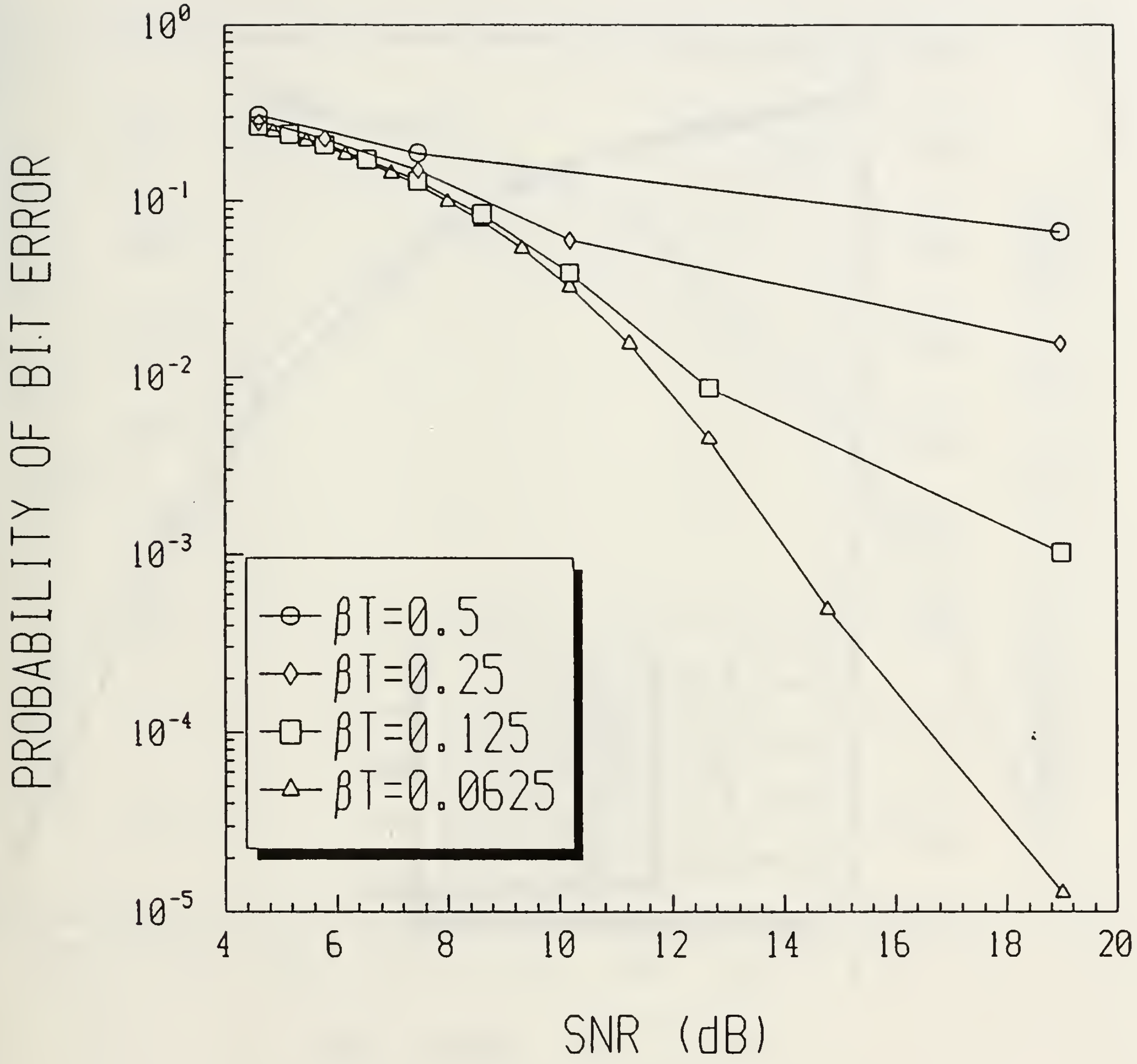

Figure 6.1: Probability of bit error for low user bit rates, threshold = 0.3

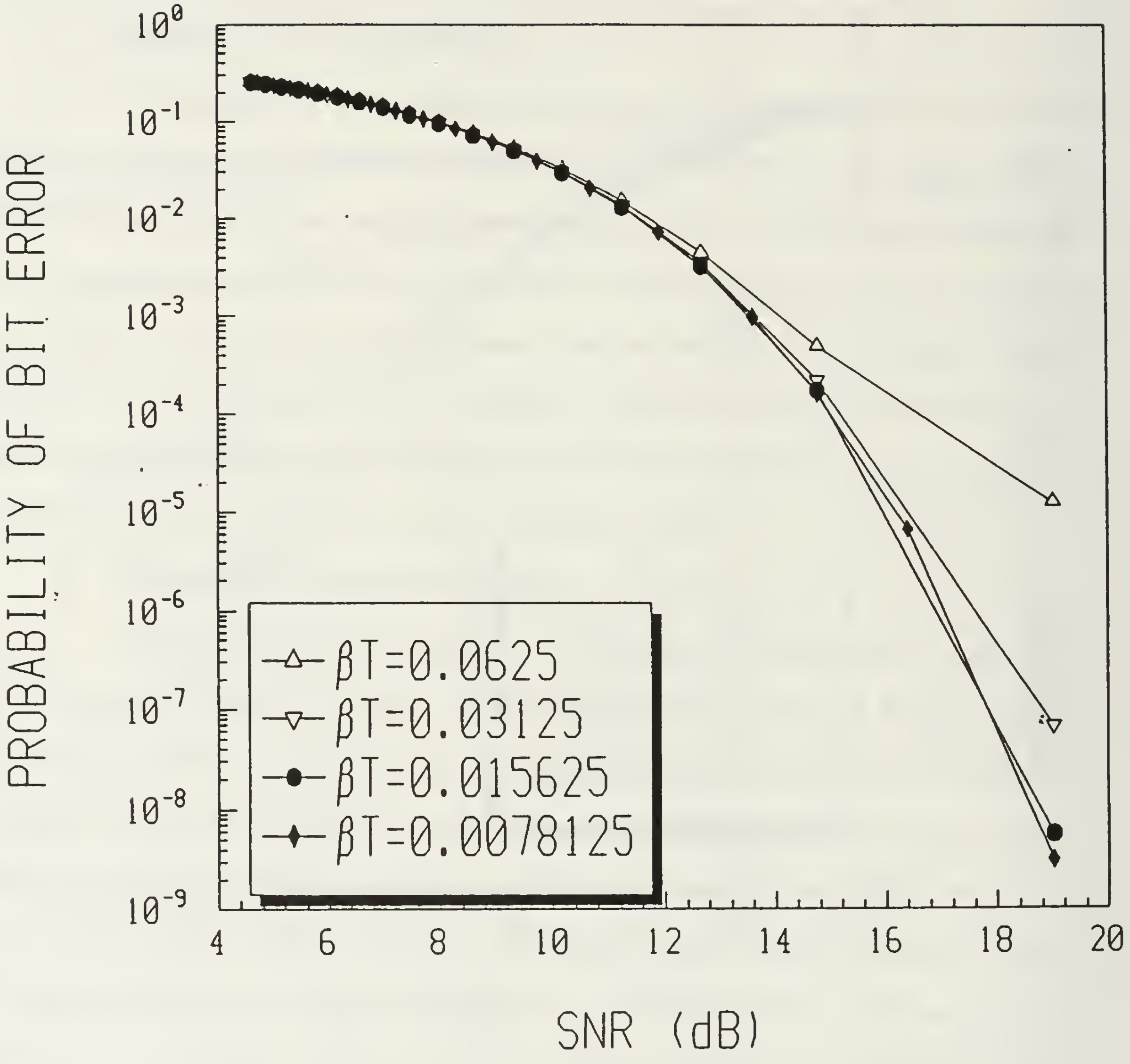

Figure 6.2: Probability of bit error for medium user bit rates, threshold = 0.3

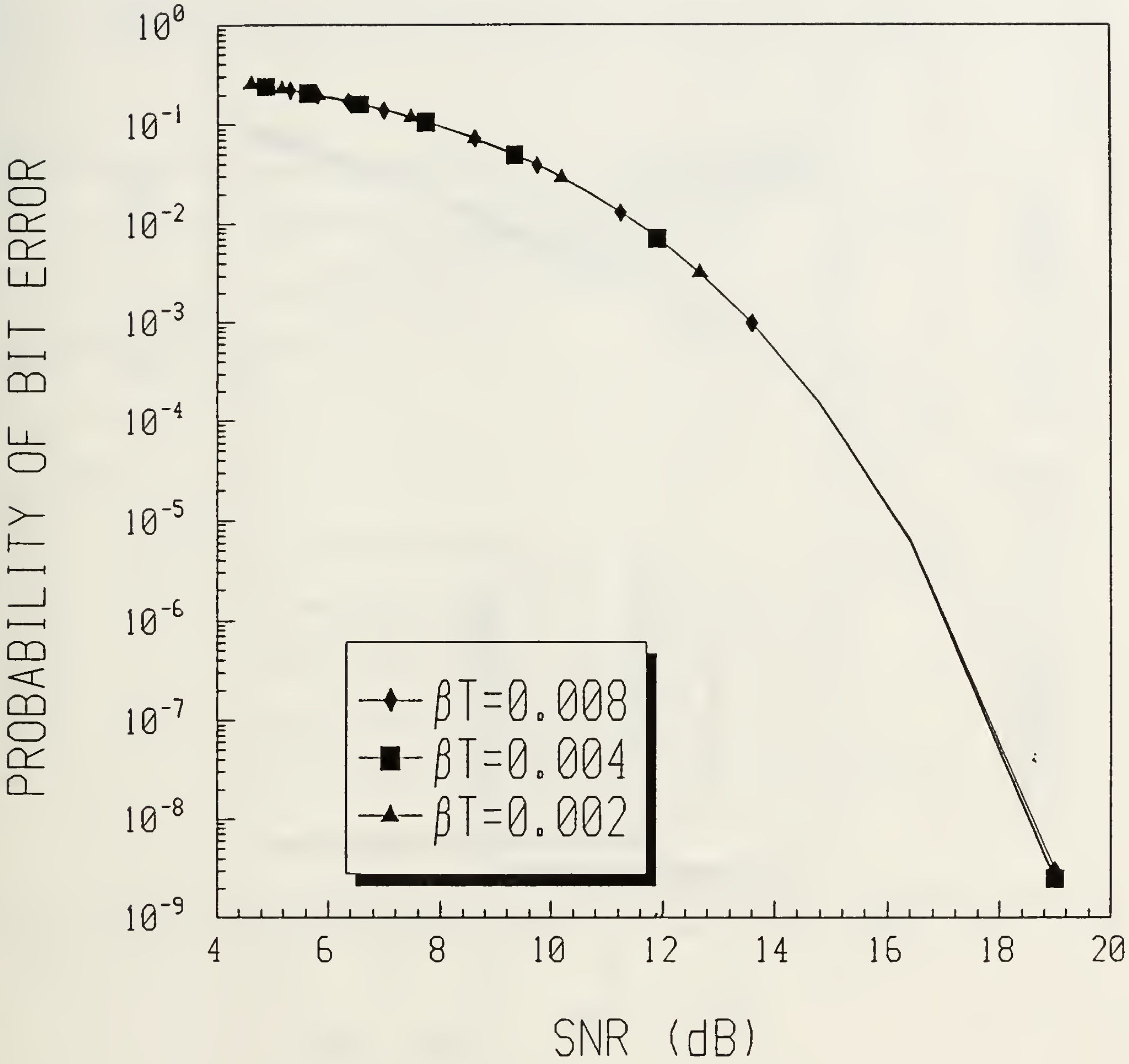

Figure 6.3: Probability of bit error for high user bit rates, threshold = 0.3

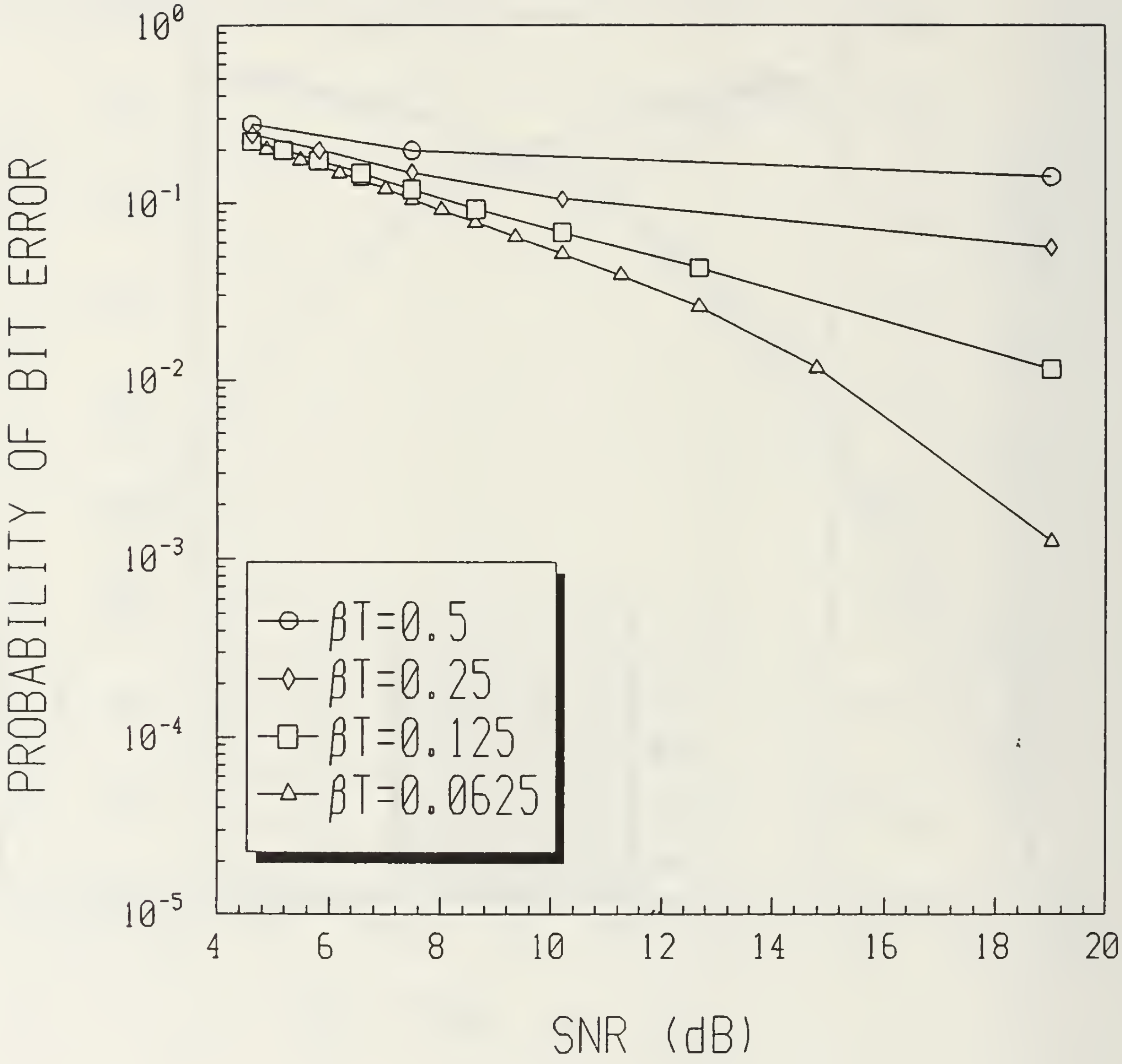

Figure 6.4: Probability of bit error for low user bit rates, threshold = 0.5

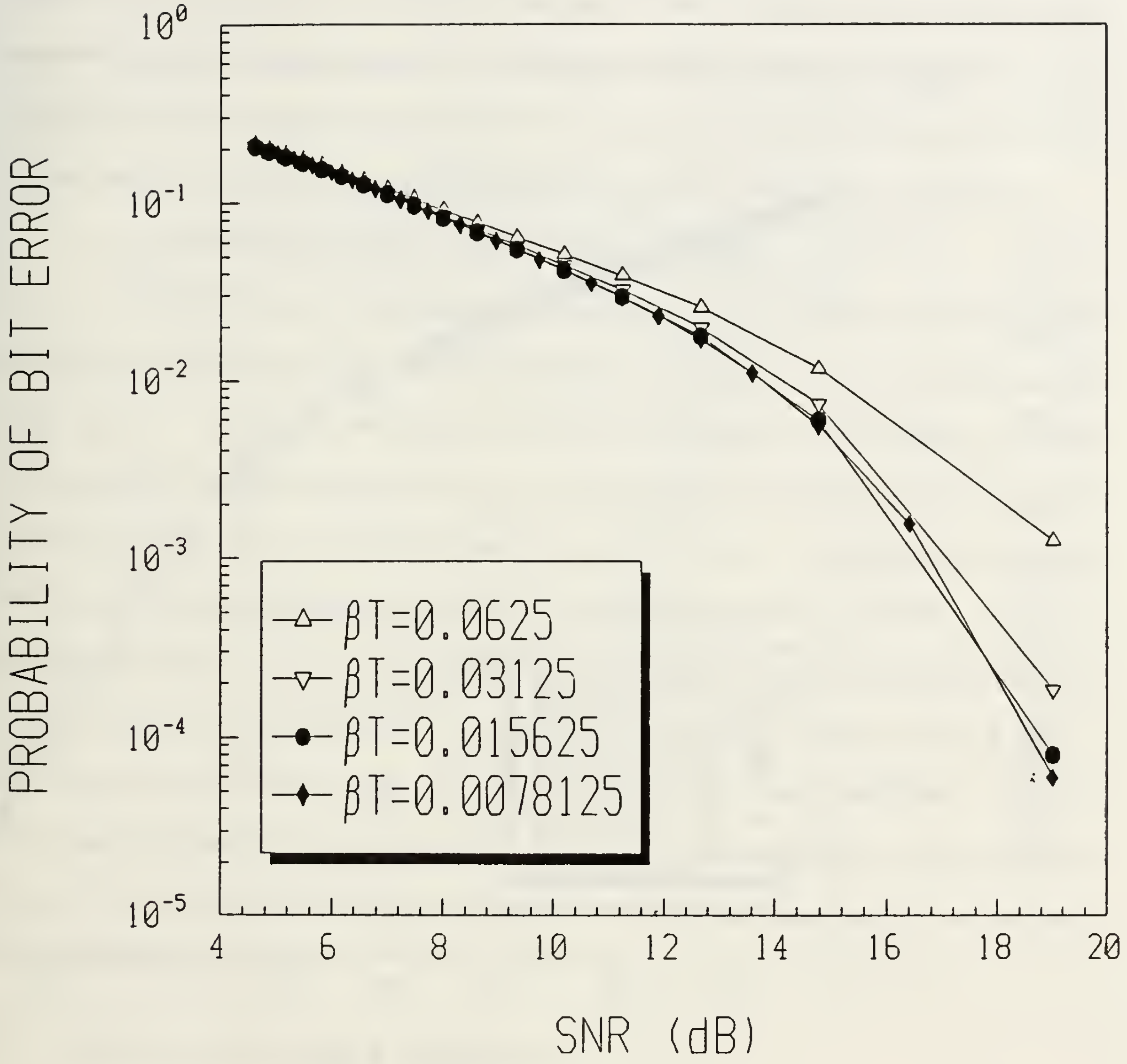

Figure 6.5: Probability of bit error for medium user bit rates, threshold = 0.5

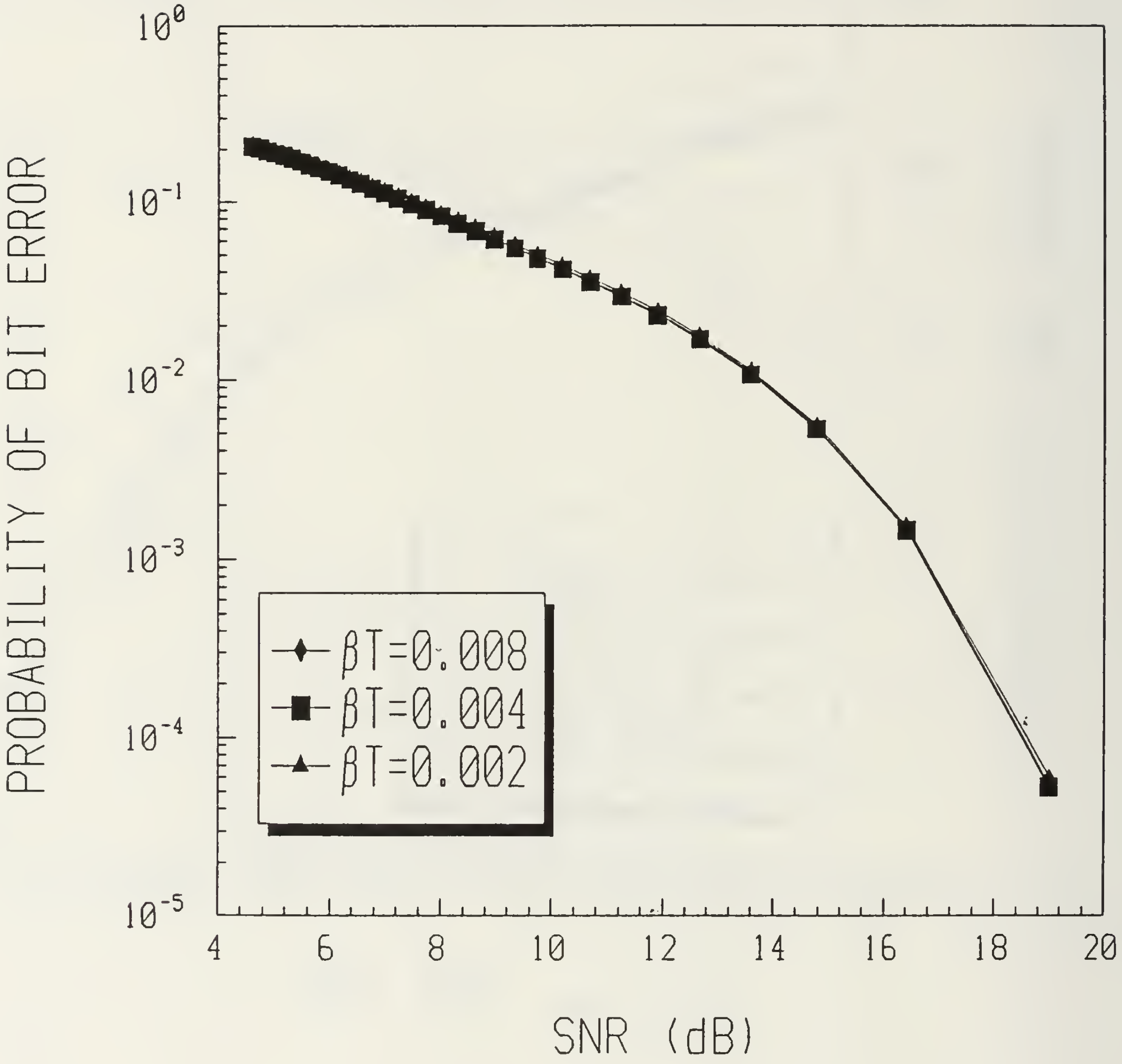

Figure 6.6: Probability of bit error for high user bit rates, threshold = 0.5

in effect. Both the SNR and the normalized decision thresholds are then varied. The results indicate that for large values of SNR, the ideal normalized threshold is in the vicinity of 0.25. This is to be expected because at large SNR, the predominant noise term is that of the laser phase noise. As the system SNR decreases, the ideal threshold shifts to the vicinity of 0.5 which indicates that the additive Gaussian noise dominates system performance. The curve illustrating this behavior is shown in Figure 6.7.

3. Comparison of Laser Phase Noise Models

The next step in the analysis is to investigate the validity of the simplified pdf for the magnitude of the random sample determined by the laser phase noise given in 5.17. Numerical evaluation of system performance was conducted under the previously stated assumptions. As a result of the conclusions contained in the previous section, the normalized threshold is set at 0.3. A comparison of system performance for the two laser phase noise models given by 5.11 and 5.17 are shown in Figures 6.8-6.10. The results indicate that 5.17 yields results comparable to those obtained with 5.11 for $\beta T_b \leq 0.1$. As expected, the results obtained with 5.17 are less accurate as βT_b gets larger. This is due to the fact that a lower bit rate leads to a longer integration interval in the IF integrator; consequently, there is a greater chance that the phase deviation is not linear over a measurement interval as assumed in the derivation of 5.17.

B. FREQUENCY SHIFT KEYING

In order to compare the performance of the optical heterodyne FSK system with that of the optical heterodyne OOK system, numerical evaluation of 5.26 is required. All assumptions with regard to the error probability floor are as before. The user bit rate is expressed in terms of the laser linewidth, and the resulting FSK curves are compared with OOK curves for the same values of βT_b over the same SNR range.

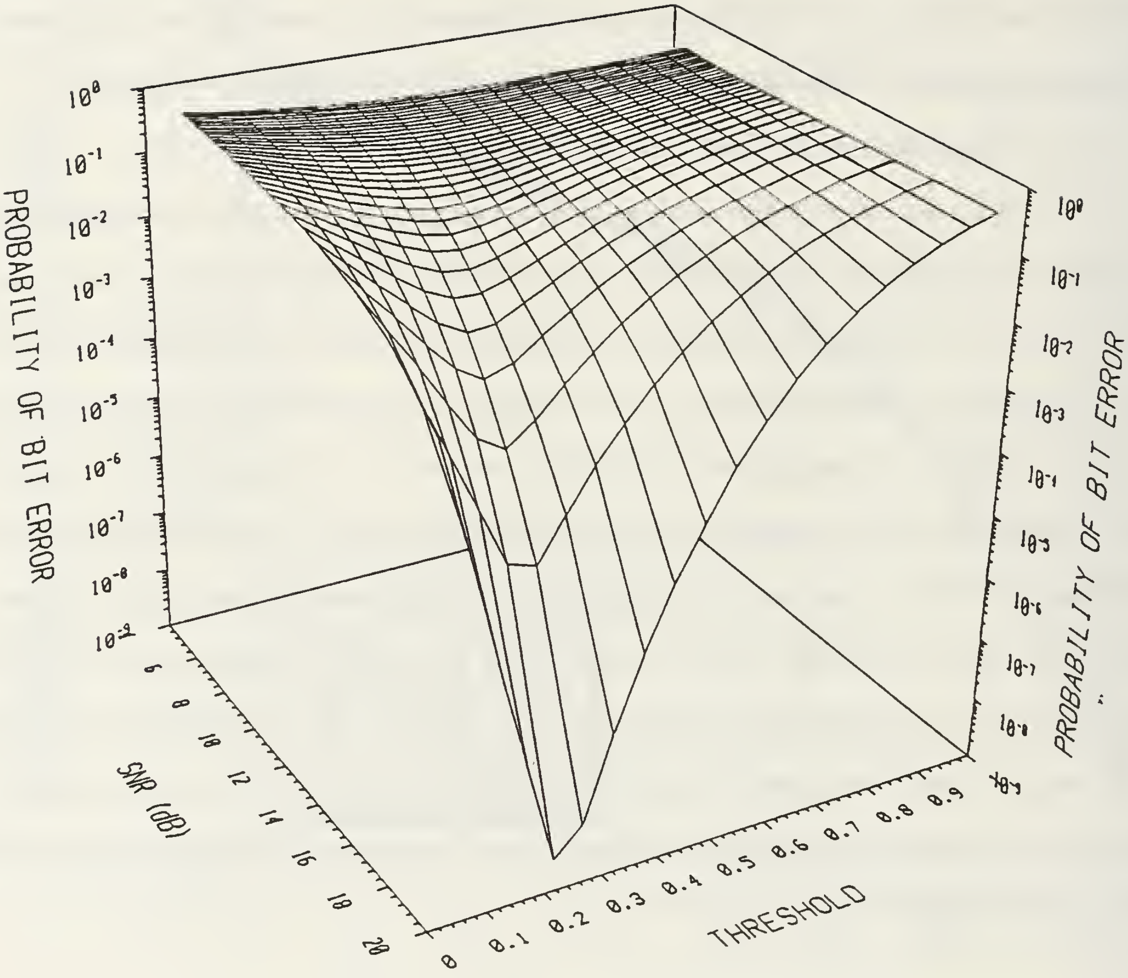

Figure 6.7: System performance over increasing system SNR and various normalized threshold settings.

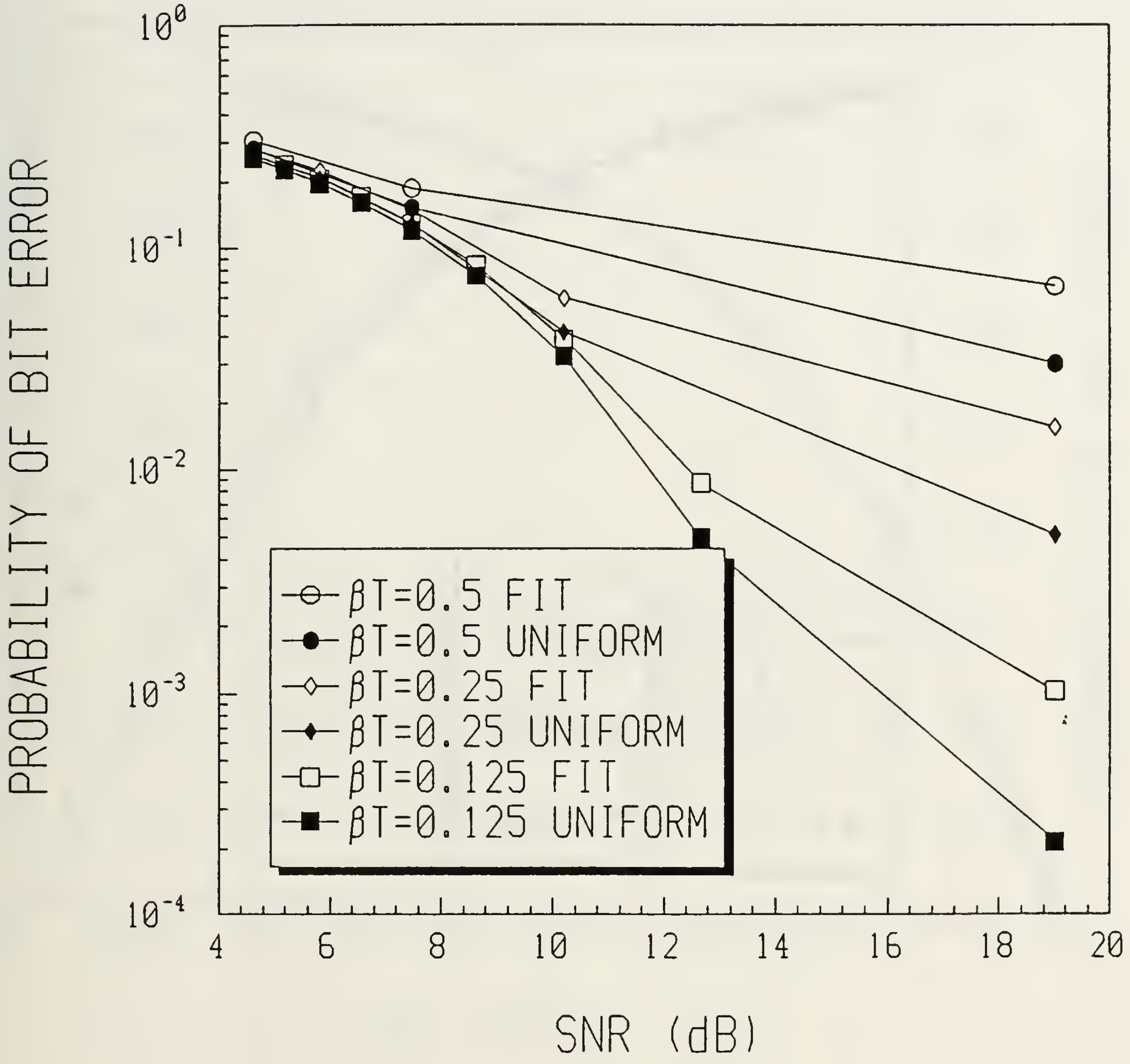

Figure 6.8: Low user bit rate comparison of laser phase noise models

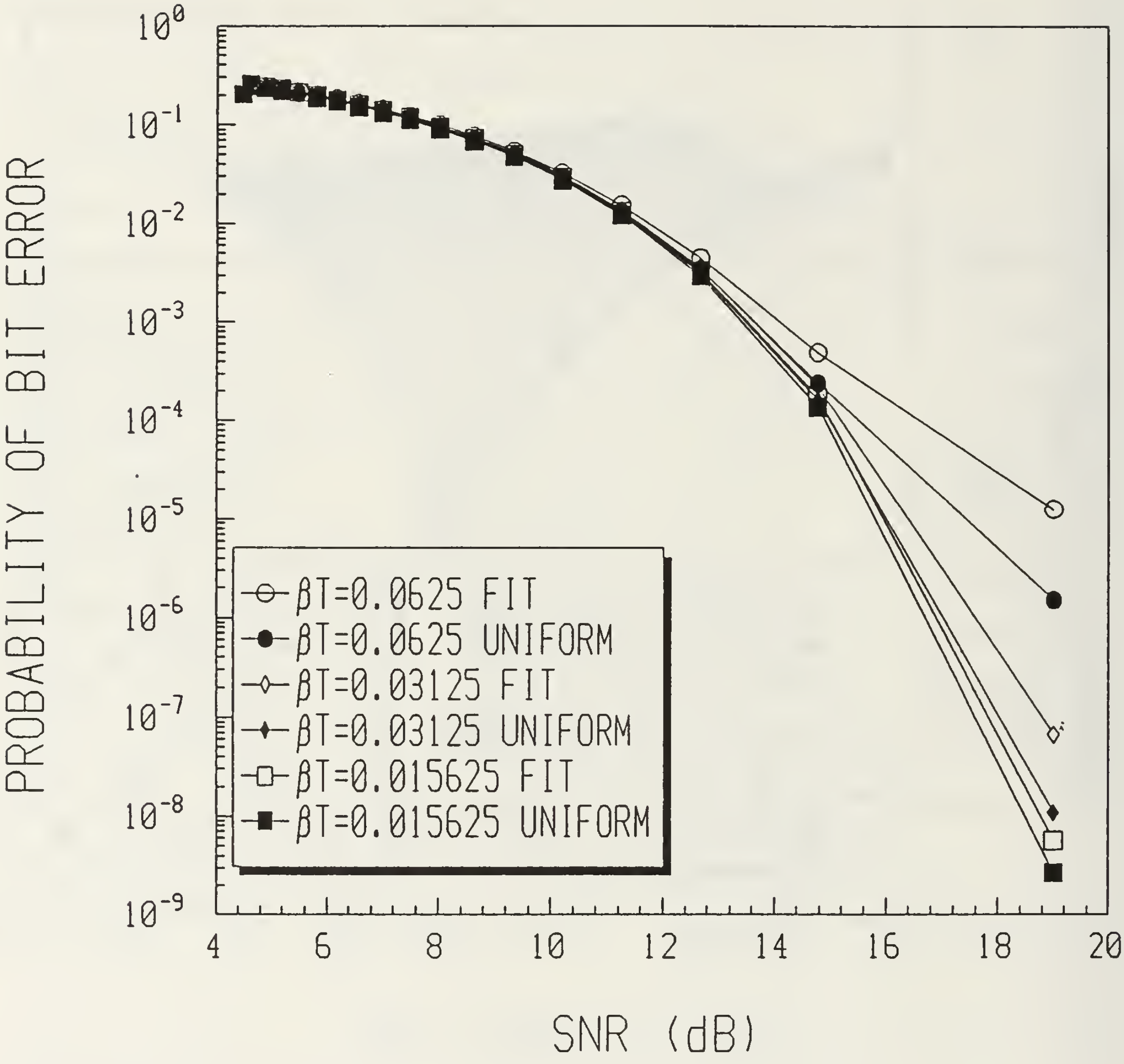

Figure 6.9: Medium user bit rate comparison of laser phase noise models

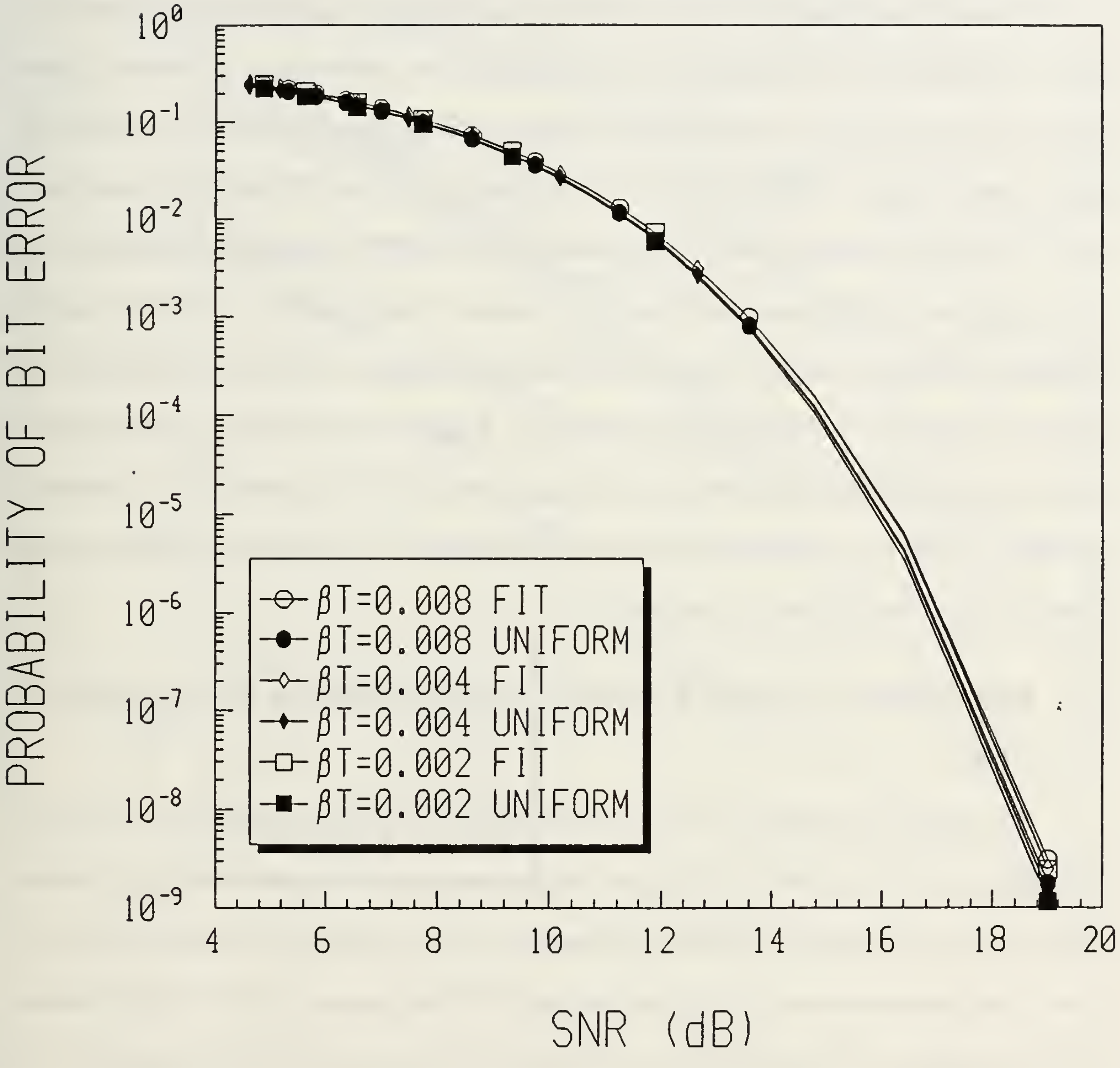

Figure 6.10: High user bit rate comparison of laser phase noise models

Based on the results obtained in the previous section, the OOK system threshold is set at 0.3. The FSK threshold is effectively 'zero' due to the nature of the FSK demodulator. The resulting comparison curves are shown in Figures 6.11-6.13.

The results indicate that the FSK system performs substantially better than the OOK system for all values of βT_b and SNR. The performance difference is most notable in Figure 6.13. At high SNR, system performance for the two systems approach one another. This is due to the fact that for large SNR the dominant noise term is the laser phase noise. The threshold in the OOK system is adjusted to 0.3 to account for the effects of the laser phase noise. The threshold in the FSK system remains unchanged; hence, at large SNR, both systems are operating near their optimal thresholds for the dominant noise source. As the SNR decreases, additive white Gaussian noise dominates system performance, and the FSK system still operates at optimum threshold while the OOK system threshold is no longer near the optimal threshold for the dominant noise term.

C. FREQUENCY SHIFT KEYING CODE-DIVISION MULTIPLE ACCESS

The results contained in the previous section indicate that optical heterodyne FSK systems are the better choice for single user optical communications systems. This dictates the selection of FSK as the modulation scheme for the proposed multiuser communications scheme to be analyzed. For the proposed FSK-CDMA system, the computation of the probability of bit error involves a numerical evaluation of 5.26 for different lengths of random user signature sequences over the range of simultaneous users the given system can support. In addition, 5.26 is evaluated for each of the two types of coding employed, random and Gold codes.

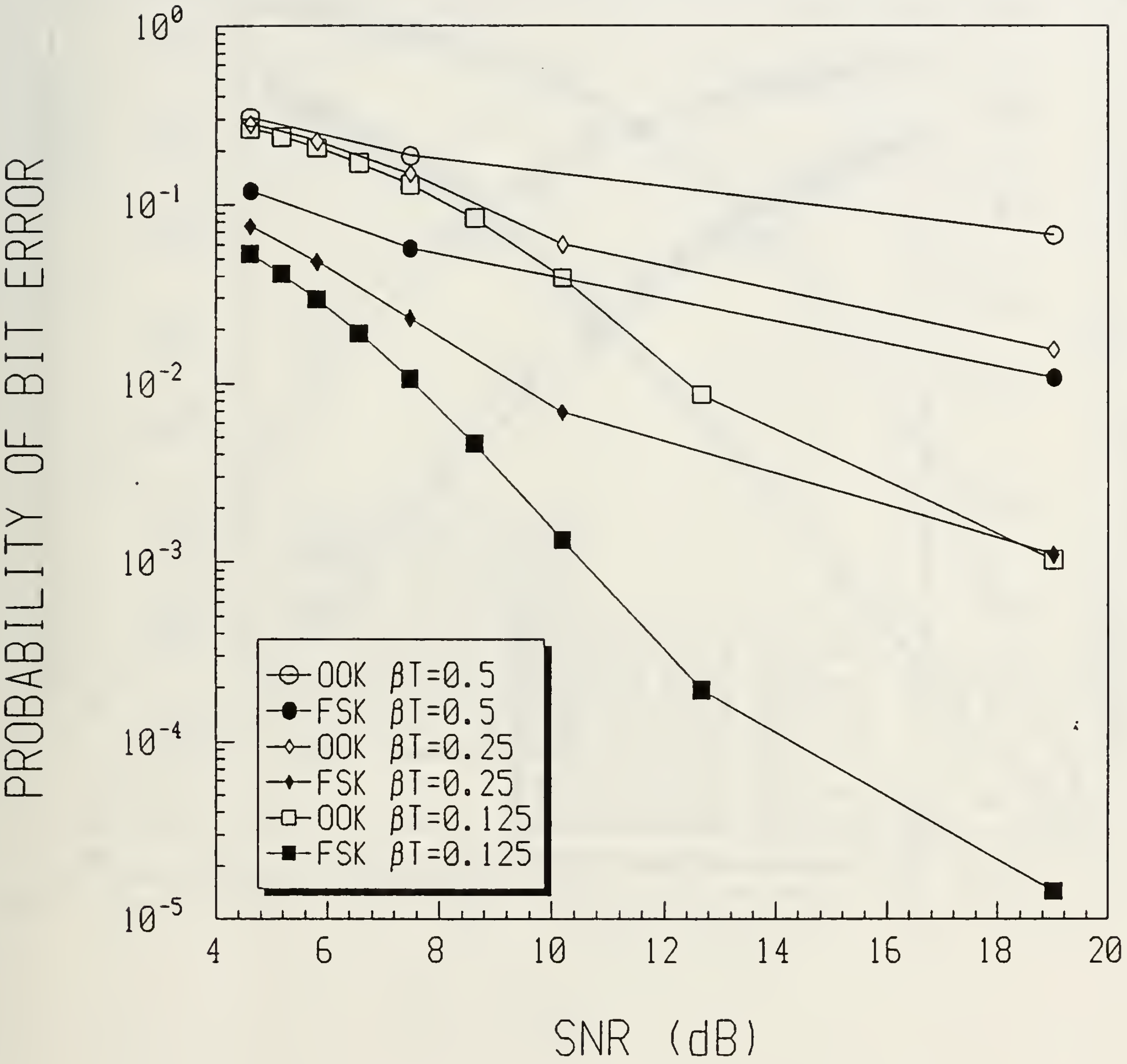

Figure 6.11: OOK versus FSK system performance for low user bit rates

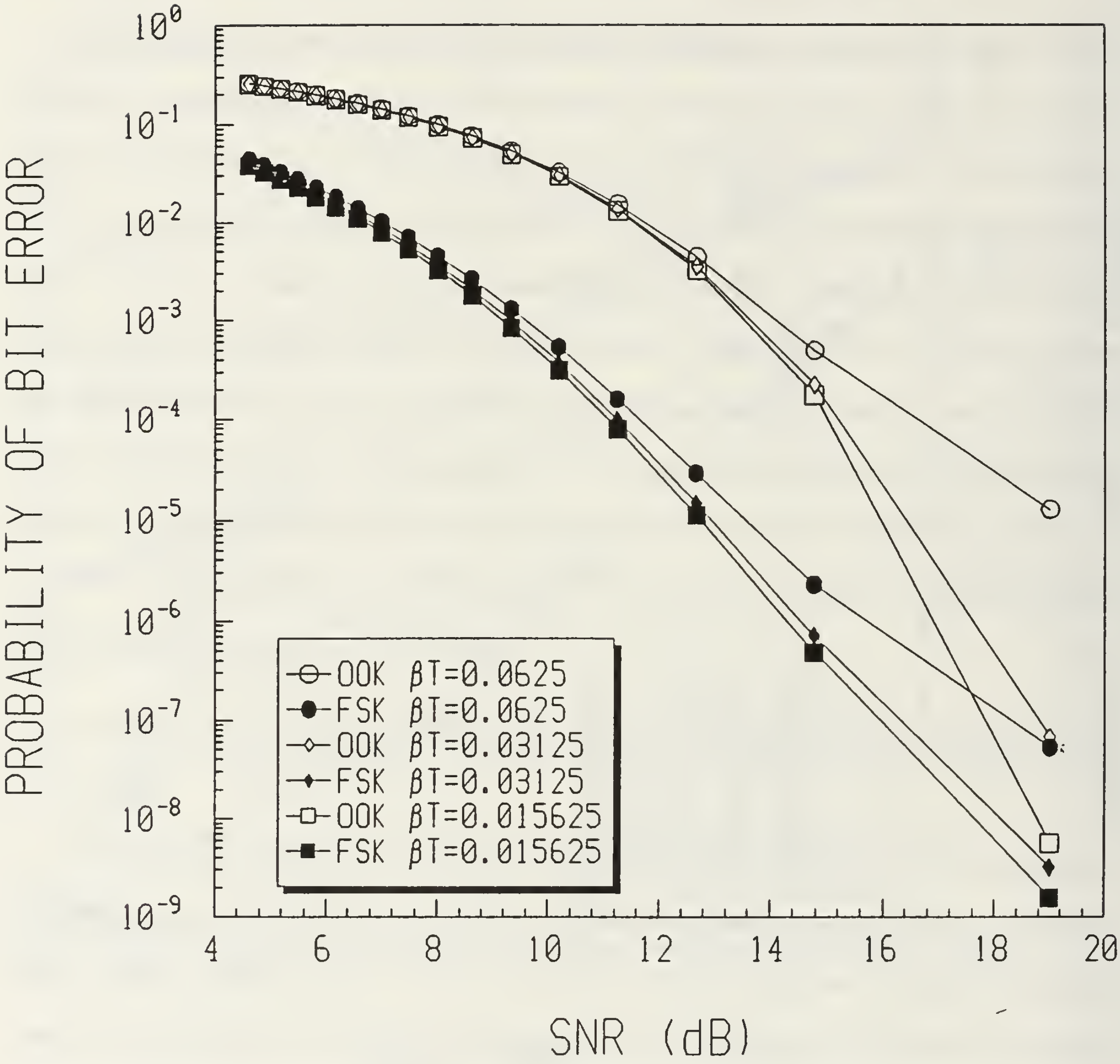

Figure 6.12: OOK versus FSK system performance for moderate user bit rates

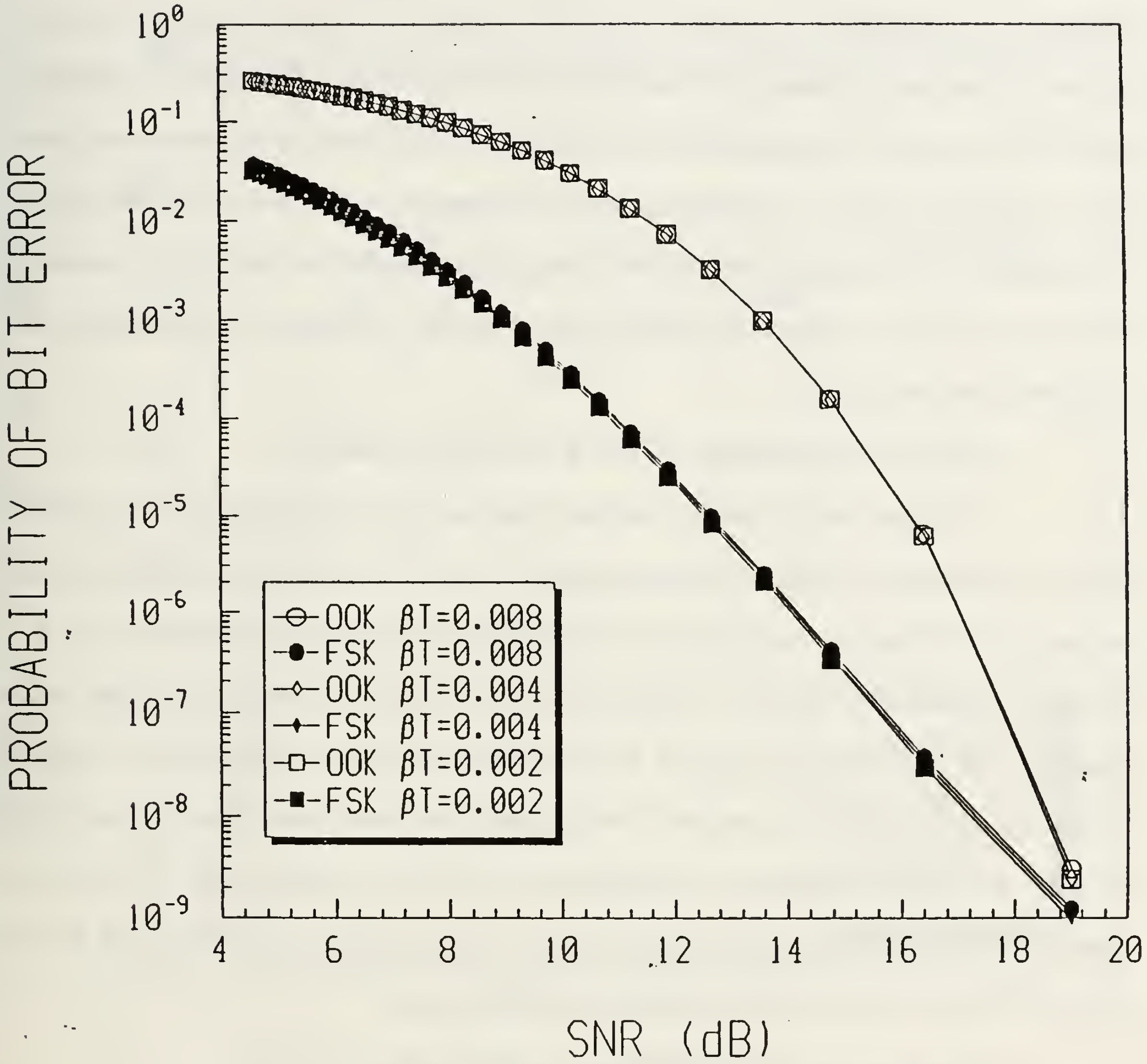

Figure 6.13: OOK versus FSK system performance for high user bit rates

As before, the receiver shot noise level is numerically fixed to establish a probability of bit error floor at 10^{-9}. Fixing the receiver shot noise level will not affect the illustrative capability of the analysis, as it is well known that spread spectrum implementation neither improves nor degrades receiver noise limited systems. In addition, in CDMA systems the multiuser noise term substantially dominates the receiver noise. As a reasonable model of current system performance, a βT_b of 0.08 is assumed. It is also assumed that the optical signal power of an individual user is normalized to unity and that the transmitter equally balances the active user signals within the composite optical signal.

1. System Probability of Bit Error Performance

The first results obtained reflect baseline system performance for optimum parameter settings. Random codes are employed, and because it was validated in the section on OOK system performance, the high frequency approximation given by 5.17 is used to model the the effect of the laser phase noise. The number of chips in the random user code is varied from 2^1 to 2^9. The resulting curves are shown in Figures 6.14-6.16. As expected, increased code lengths allow more simultaneous users in the channel for a given reduction in probability of bit error performance. These curves also show the standard CDMA characteristics in that they are fairly steep for low number of users and flat at high usage levels [Ref. 16].

2. Comparison of Gold Codes and Random Codes

The final aspect of system operation to be explored is a comparison of Gold coding and random coding. Numerical evaluation of system performance was conducted for both codes over varying numbers of users. The comparison curves are shown in Figures 6.17-6.18. These figures verify the fact that system performance is only slightly degraded by the use of Gold codes as opposed to random codes. The degradation produced by the use of Gold codes has less effect on system performance

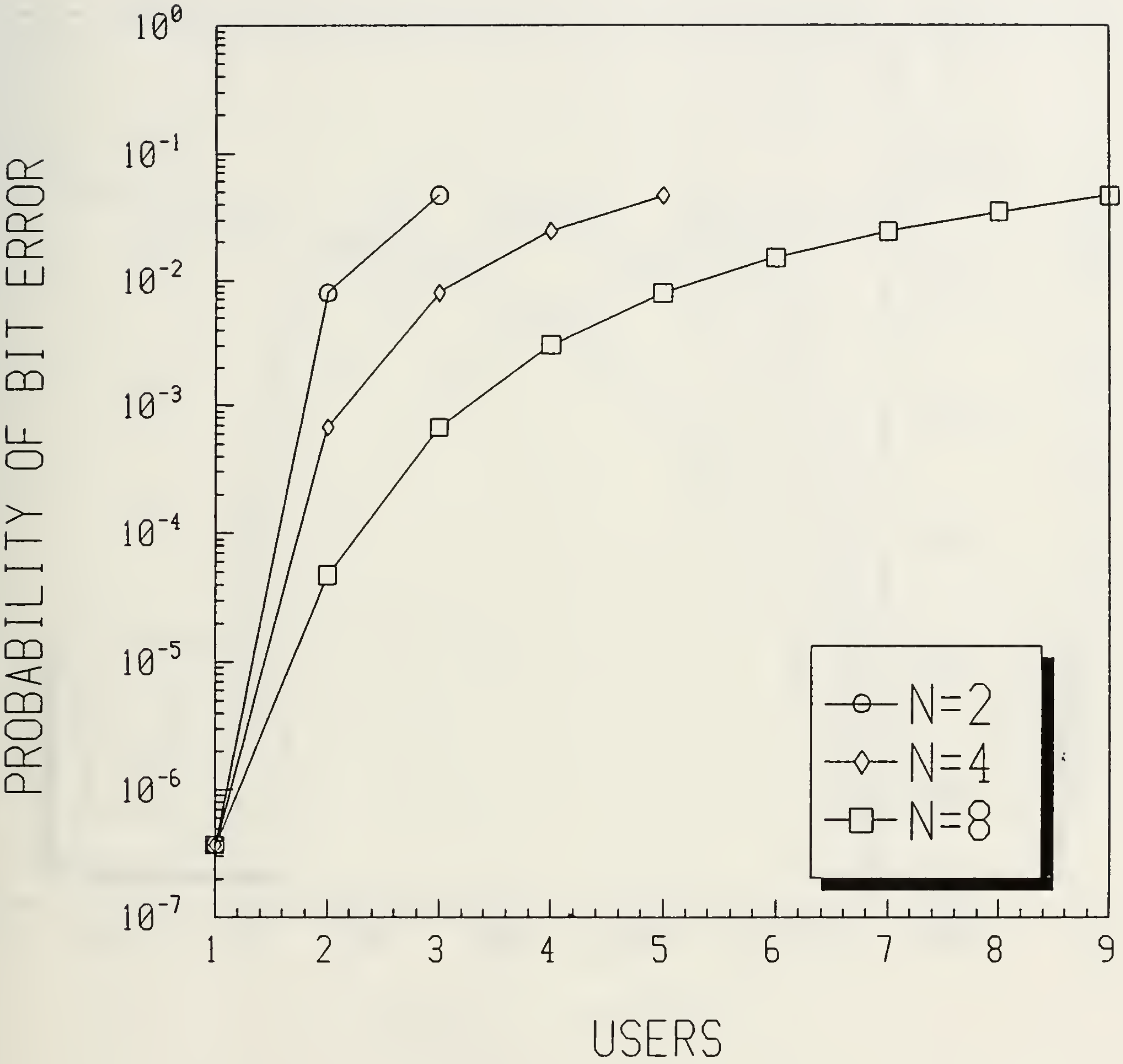

Figure 6.14: Probability of bit error for low order random codes

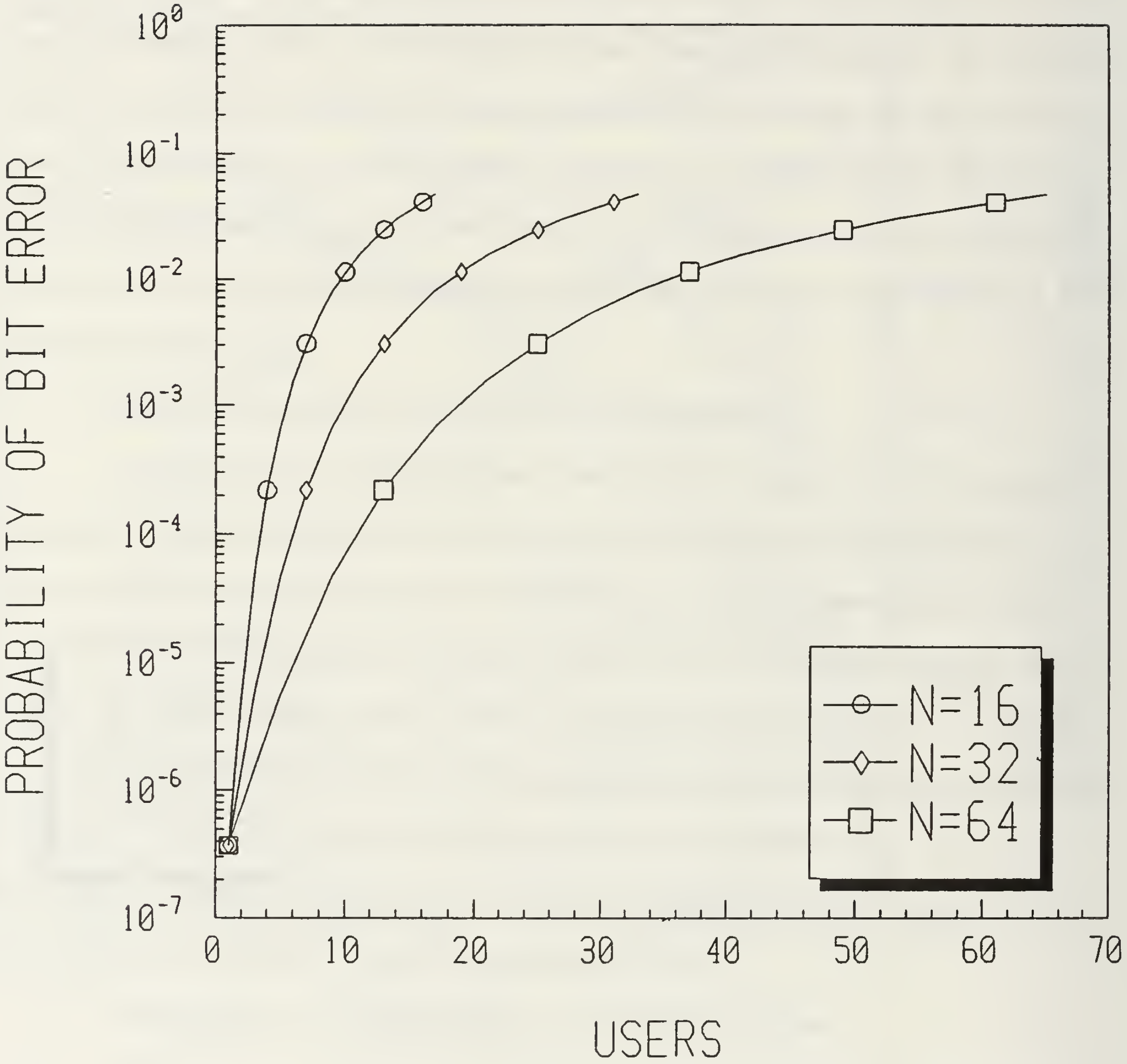

Figure 6.15: Probability of bit error for medium order random codes

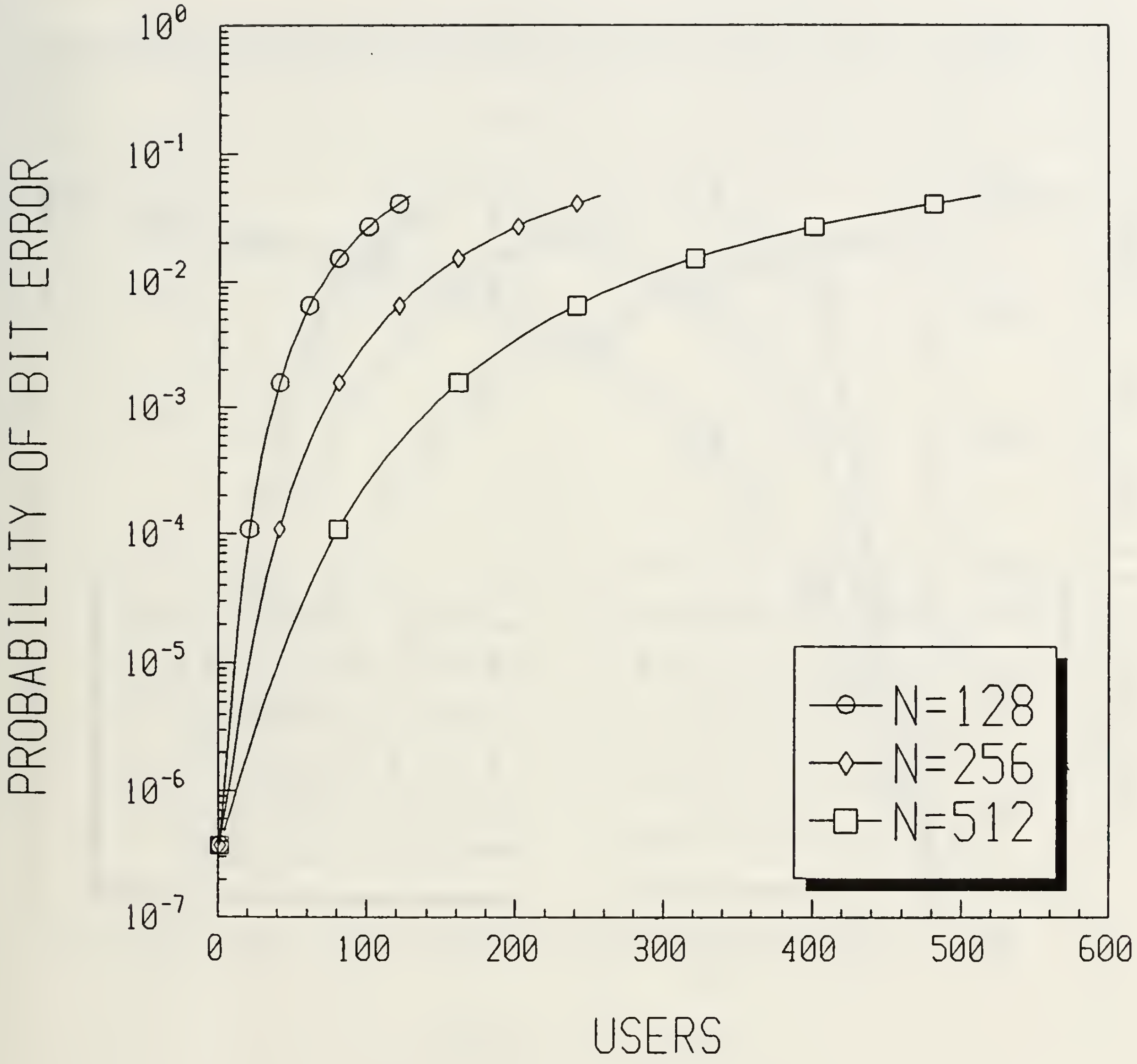

Figure 6.16: Probability of bit error for high order random codes

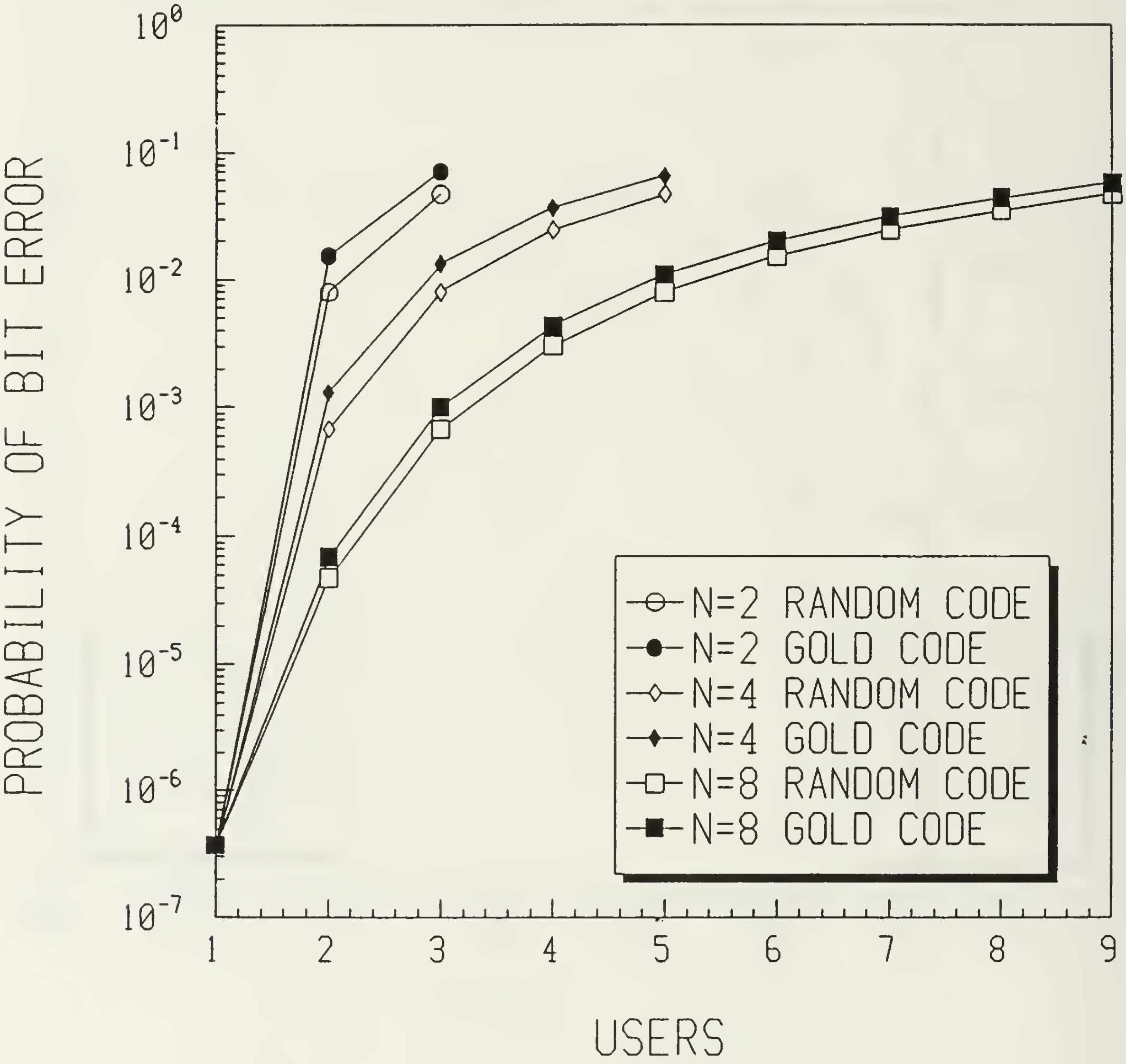

Figure 6.17: Low order code comparison of random and Gold codes

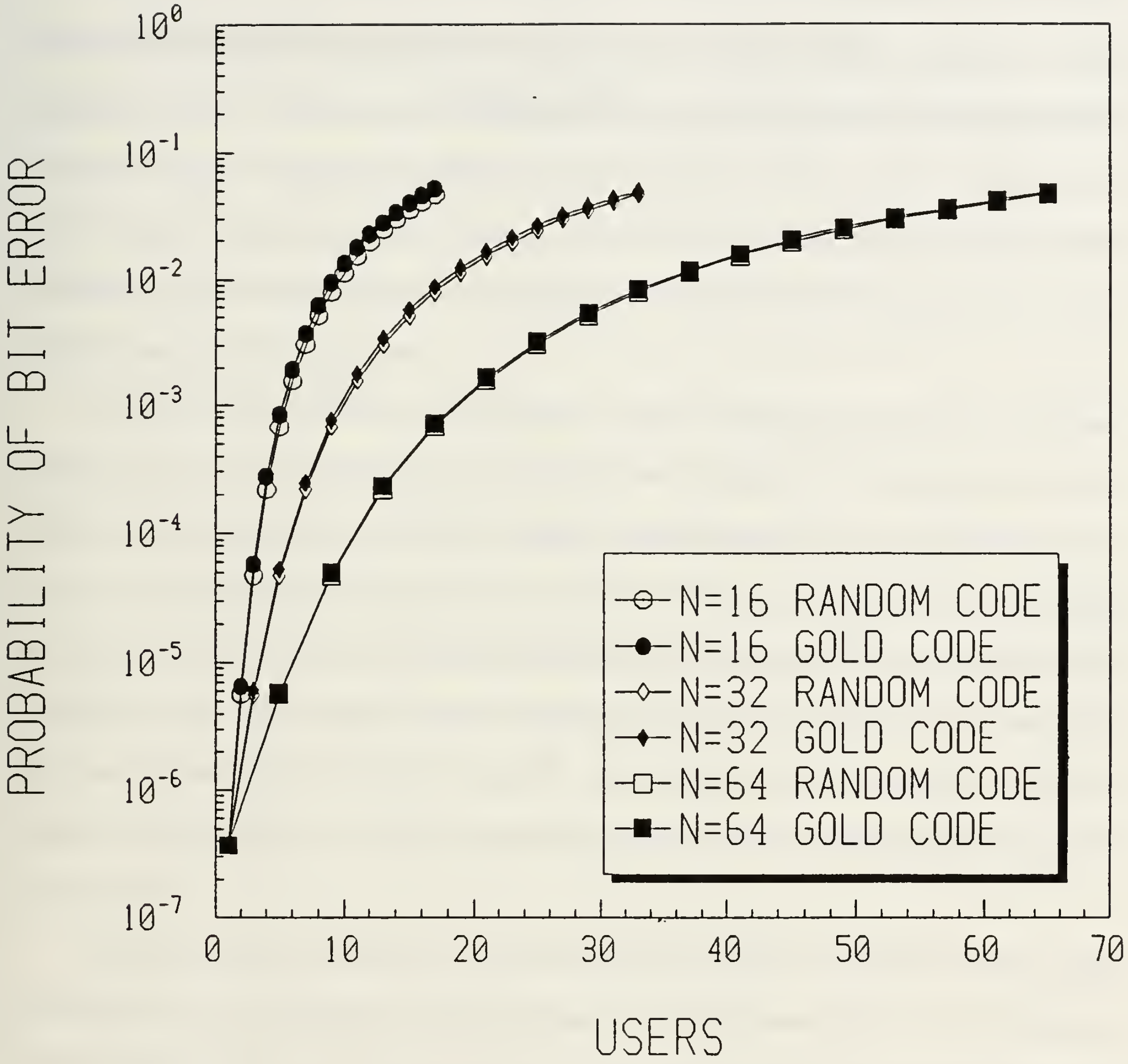

Figure 6.18: Medium order code comparison of random and Gold codes

as the code length increases. This result is important as it shows that the results obtained calculating system performance using impractical random codes are valid for systems employing Gold codes.

The numerical results reported in this chapter are used to draw the overall conclusions presented in the next and final chapter.

VII. CONCLUSIONS

Future optical communications systems will service many simultaneous high data rate users. Current optical communications systems employ intensity modulation and WDM to obtain multiuser communications. Most current research in the field of optical communications systems is directed toward the analysis of these weakly coherent low data rate systems. This thesis has presented an extensive study of the performance of future systems.

The primary conclusion of this thesis is that at high user bit rates, the laser phase noise has very little impact on system performance. As the user bit rate increases, the laser phase noise effect on system performance for a given SNR decreases. At user bit rates greater than about 128 times the laser linewidth, the laser phase noise has almost no effect and system performance is dominated by the additive white Gaussian noise. The results are also presented for various values of SNR, thresholds, required probability of bit error, and βT_b so that they may be generally applied in system design. Any one of the required parameters may be determined given the other three.

The secondary conclusion of this thesis is that optical heterodyne FSK systems outperform optical heterodyne OOK systems. Noncoherent FSK and noncoherent OOK detection systems corrupted only by Gaussian noise exhibit similar performance [Ref. 4]. The optical analogs of these systems do not due to the dependence of the optimum OOK threshold on the laser phase noise.

Analysis of WDM systems has been extremely difficult in the past because of the mathematically complex expression required to model the random variable representing the laser phase noise at low system bit rates. The approximation for the random variable describing the effect of laser phase noise in the high bit rate systems derived in this thesis approaches standard Gaussian behavior. In addition, the laser phase noise model derived in this thesis improves on other models in that it is not based on an empirical derivation but on the actual behavior of the laser. The high frequency model of the random variable representing the laser phase noise derived in this thesis is therefore more useful in mathematical simulations as it can be easily rederived and modified as required.

In the design of optical heterodyne OOK systems, the ideal normalized threshold to be used must be considered. Obviously, the ideal system would have an adaptive threshold device at the comparator to provide optimum performance [Ref. 5]. Such a device may not be practical to implement, and this thesis shows that if the threshold is to be fixed at a particular level, then it should be set at about 0.3 of the total bit energy. The probability of bit error as a function of both the normalized threshold and system SNR is shown in Figure 6.7. The probability of bit error is most sensitive to threshold variations when the system is operating at large SNR. In this case the optimum threshold is less than 0.25. As the system SNR decreases, threshold sensitivity decreases, and the optimum threshold approaches 0.5. As a result, the penalty is much less for having the threshold set at 0.3 when the system operates at low SNR than it is for having the threshold set at 0.5 when the system SNR is large.

To improve overall optical communications system performance, the application of CDMA spread spectrum techniques to a standard optical heterodyne FSK system employing Wavelength Division Multiplexing (WDM) to obtain multiple simultaneous user capabilities is proposed. This system can greatly improve system user capacity without a substantial increase in the probability of bit error.

This work has also demonstrated the validity of the assumption that the results obtained modelling the spreading codes as totally random sufficiently reflect the expected performance of systems employing Gold codes.

As a final illustration of system improvement realized by the proposed FSK-CDMA communication scheme, a possible future system is analyzed for CDMA multiuser probability of bit error. It is assumed that $\beta T_b = 0.08$ and the data stream is spread by a code length of 2^{15}. The curve representing system behavior is shown in Figure 7.1. As shown, if the system operates as a standard WDM channel, (that is, with only one user), the system performs at the best probability of bit error performance possible, 10^{-7}. If the system designer desires multiple user capability and is willing to accept a degradation in performance from 10^{-7} to 10^{-6}, then approximately 1200 users can simultaneously use the channel.

Future research in the analysis of optical heterodyne communications systems is needed primarily in the spread-spectrum process. This work analyzes a system in which the data stream is spread and collapsed electronically. Other works propose spreading and despreading the data stream optically. One method proposes a system in which an on-off keyed (OOK) data signal modulates a semiconductor laser, and the optical pulse train is spread with a lithium niobate crystal phase modulator [Ref. 17]. The spread optical signal is despread by a similar phase modulator and then detected by a photodetector. Another method of optically spreading the user data stream is through the use of optical orthogonal codes (OOC) [Ref. 18]. OOCs consist of a pseudorandom series of 'ones' and 'zeros'. A laser light transmission represents a 'one' and no transmission represents a 'zero'. These OOCs are then despread with a fiber optic tapped delay line or matched filter at the receiver. The disadvantage of the OOC system is the fact that the OOCs cannot be optically manipulated to add to zero as can the $+1, -1$ electronic codes. As a result, the cross-correlation

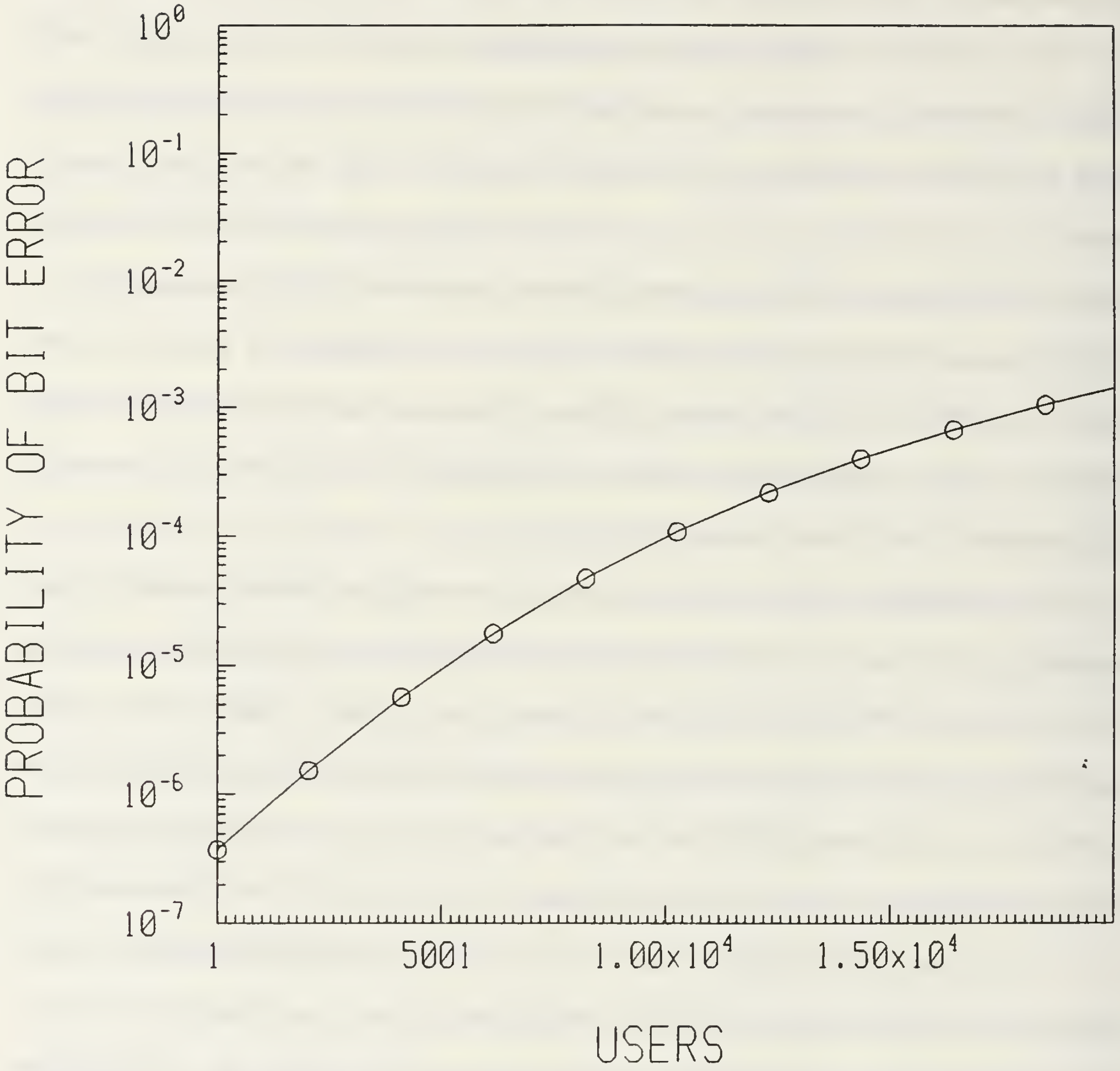

Figure 7.1: Probability of bit error for random coded FSK-CDMA system, code length 2^{15}

functions of these codes have significantly greater magnitude, and the multiuser noise for similar code lengths is much greater. Because of the high multiuser noise, greater code lengths must be used to achieve resonable system performance. Further work in the comparison of optically spread systems should be pursued to establish which system is more practically implemented.

Finally, this work predicts the performance of a theoretical system. Nothing can replace the actual construction and testing of such a system to verify performance. Logical assumptions are made in the mathematical and numerical analysis of this system, but as detailed in Chapter II, many physical limitations introduced by the individual system components may drastically affect system performance. Theoretical works such as this one can only indicate which system configurations show the most promise. Clearly, the implementation of high speed OOK, FSK, and FSK-CDMA is a potentially promising way to improve optical fiber communication system performance.

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